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ABSTRACT

This course in electrical power and illumination systems is one of 16 courses in the Energy Technology Series developed for an Energy Conservation-and-Use Technology curriculum. Intended for use in two-year postsecondary technical institutions to prepare technicians for employment, the courses are also useful in industry for updating employees in company-sponsored training programs. Comprised of eight modules, the course is designed to provide the student with a practical knowledge of electrical power, distribution systems, and illumination systems. The students practice electrical measurement, wiring methods, illumination measurement, and circuit control and are provided with an overview of the parts of the electrical distribution system. Written by a technical expert and approved by industry representatives, each module contains the following elements: introduction, prerequisites, objectives, subject matter, exercises, laboratory materials, laboratory procedures (experiment section for hands-on portion), data tables (included in most basic courses to help students learn to collect or organize data), references, and glossary. Module titles are Efficiencies of Electrical Power Distribution Systems, Electrical Power Transmission and Distribution, Industrial Electrical Distribution, Residential Electrical Distribution, Electrical Energy Management, Fundamentals of Illumination, Light Sources, and Efficiency in Illumination Systems. (YLB)

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ELECTRICAL POWER AND ILLUMINATION SYSTEMS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
601 LAKE AIR DRIVE
WACO, TEXAS 76710

APR. 1981

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PREFACE

ABOUT ENERGY TECHNOLOGY MODULES

The modules were developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment and are useful in industry for updating employees in company-sponsored training programs. The principles, techniques, and skills taught in the modules, based on tasks that energy technicians perform, were obtained from a nationwide advisory committee of employers of energy technicians. Each module was written by a technican expert and approved by representatives from industry.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify, and define, rather than words with many interpretations, such as know, understand, learn, and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Laboratory Materials, which identify the equipment required to complete the laboratory procedure.

Laboratory Procedures, which is the experiment section, or "hands-on" portion, of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

References, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of prestated objectives.

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MODULE PI-07 Light Sources

MODULE PI-08 Efficiency in Illumination Systems

INTRODUCTION TO ELECTRICAL POWER AND ILLUMINATION SYSTEMS

Most technicians are not required to be electrical power specialists. However, many technicians must know about electrical power as it relates to energy efficiency.

This relationship includes areas such as energy conservation, energy efficiency, basic system operation, function of components, basic wiring skills, codes, safety, power management, and utility rate schedules.

Technicians must also know the principles of illumination, light sources, kinds of lighting systems and controls, how to efficiently use lighting, how to make and implement light and power budgets, what efficient residential wiring is — and how to do basic calculations on all the above.

Electrical Power and Illumination Systems accomplishes these objectives. In addition, students also practice electrical measurement, wiring methods, illumination measurement, circuit control — and are provided with an overview of the parts of the electrical distribution system.

Module PI-01, "Efficiencies of Electrical Power Distribution Systems," describes basic characteristics of reactive a.c. circuits, calculation of power factor and voltage drop on power lines, and corrective measures common in industry. PI-01 also gives a brief overview of power distribution systems.

Module PI-02, "Electrical Power Transmission and Distribution," describes transmission and distribution systems with particular emphasis on efficiency and control in those systems. The second module also familiarizes the student with large equipment and circuit components.

Module PI-03, "Industrial Electrical Distribution," discusses industrial power system layout, safety, controls, circuit protection, reliability, and energy efficiency as it relates to the industrial sector.

Module PI-04, "Residential Electrical Distribution," surveys the characteristics of safe wiring systems based on the National Electrical Code. The fourth module also includes information about wiring practices, components, factors influencing wiring safety, and factors influencing wiring efficiency.

Module PI-05, "Electrical Energy Management," incorporates information from previous modules, explains the hows and whys of utility rates, and details how to reduce the monthly utility bill. The fifth module also explains how to reduce electrical energy use and how to purchase power at a discount.

Module PI-06, "Fundamentals of Illumination," provides the student with the basic principles of illumination, including topics such as the spectrum, inverse square law, reflection, light measurement, required light levels, and quality of illumination.

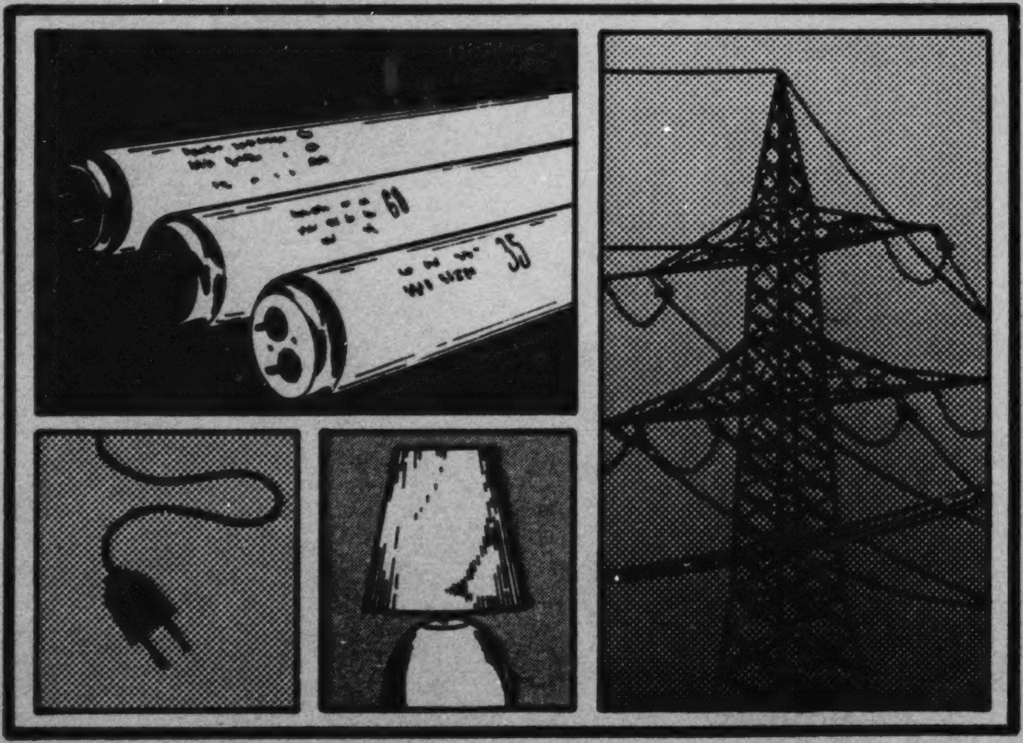
Module PI-07, "Light Sources," discusses the characteristics of light sources and how light sources may be applied. The efficiency, rated lifetime, light depreciation with aging, and spectral characteristics of all common light sources are also described in the seventh module.

Module PI-08, "Efficiency in Illumination Systems," addresses the efficient use of lighting in residential, commerical, and industrial applications. In addition, the eighth module explains efficient lighting design and maintenance of illumination systems, and provides tips on saving energy and completing a cost analysis of lighting systems.

The purpose of Electrical Power and Illumination Systems is to acquaint the student with the major areas of the field, not make the student an expert in any particular area. The student should emerge from the course a more diversified technician with the ability to converse intelligently with specialists in each related area.

ENERGY TECHNOLOGY
CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-01
EFFICIENCIES OF ELECTRICAL POWER DISTRIBUTION SYSTEMS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

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INTRODUCTION

Electrical energy is popular for a wide range of applications. This is because of the ease with which it can be converted to other forms of energy (such as heat, light, or motion) and because of the ease of distribution of electrical energy.

In generating plants, mechanical energy is converted to electrical energy by large alternators. The prime mover of the alternator may be a water turbine, a windmill or a steam turbine. Boilers for steam plants are most often fired with fossil fuels, but nuclear reactors and geothermal sources are also used.

No matter what original energy source is used, the output energy is alternating current electrical energy that can be transmitted over large distances for remote applications.

The efficient use of electrical energy requires a sophisticated distribution system that can deliver power to the point of use with minimum losses. This module, "Efficiency of Electrical Power Distribution Systems," discusses factors affecting the efficiency of electrical distribution systems, as well as methods used to reduce power losses. A review of a.c. circuit analysis is included; example problems illustrate methods of improving system efficiency by correcting the power factor.

In the laboratory, the student will construct simple a.c. circuits and determine power factors and efficiencies.

PREREQUISITES

The student should have mastered basic physics and d.c. and a.c. circuit analysis. The student should have also taken, or be taking, Electromechanical Devices.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe a typical electrical power distribution system, including the voltages present in each section of the system.
2. Explain the loss of an electrical power system and the reasons for voltage drop at high loads.
3. Given the frequency of an a.c. circuit and the values of capacitance and inductance in the circuit, determine the values of inductive reactance and capacitive reactance.
4. Given the values for resistance, inductive reactance, capacitive reactance, frequency and voltage in a series or parallel a.c. circuit, determine the current and voltage of each component.
5. Explain the following terms:
   a. Power factor
   b. Apparent power
   c. True power
   d. Reactive power
6. Given three of the following quantities for a single-phase or three-phase a.c. circuit, determine the fourth:
   a. True power
   b. Power factor

    c. Current
    d. Voltage
7. Given the current, voltage, and power factor of an a.c. circuit and the resistance of the power delivery lines, determine the following:
    a. Shunt capacitance for a power factor 1.0
    b. Voltage drop in lines without power factor correction
    c. Voltage drop in lines with power factor correction
8. Given the current, voltage, and power factor of an a.c. circuit and the resistance of the power delivery lines, determine the following:
    a. Series capacitance for power factor of 1.0
    b. Voltage delivered to the RL load
    c. Voltage drop in the power lines
9. Construct RL circuits in the laboratory and correct the power factor to 1.0 using both series and parallel capacitors.

A.C. POWER SYSTEMS

An a.c. power system consists of a generating station where mechanical energy is transformed into electrical energy by a large alternator, a distribution system that supplies the electrical energy to the point of application, and devices that convert electrical energy to other forms for application.

Efficient use of electrical energy depends upon efficient energy convertors (alternators, motors, light sources) and a low loss distribution system. Alternators and motors are discussed in detail in Electromechanical Devices. Alternator and motor characteristics considered in this course include only electrical load characteristics.

The first four modules of this course discuss the components and efficiencies of electrical power distribution systems. The fifth module is concerned with management of electrical loads for increased efficiency and reduced energy costs. The last three modules discuss light sources and the efficient use of lighting.

This module deals with the characteristics of a.c. electrical circuits that affect power loss (and, thus, the efficiency of the circuit), as well as basic techniques used to minimize loss.

TRANSMISSION AND DISTRIBUTION OF ELECTRICAL POWER

Figure 1 shows an electrical power distribution system and the customers it serves. Power is generated in the power house at a voltage of 20,000 volts. Step-up trans-

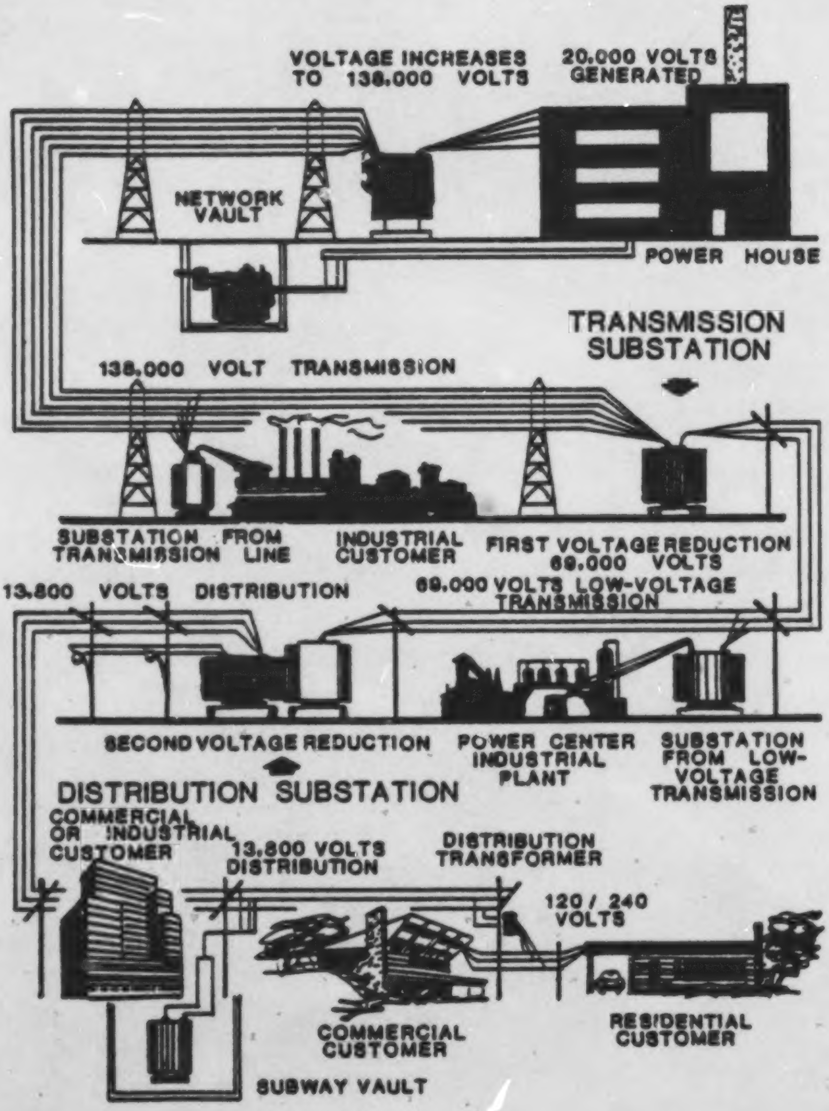

VOLTAGE INCREASES TO 138.000 VOLTS
20.000 VOLTS GENERATED
NETWORK VAULT
POWER HOUSE
TRANSMISSION SUBSTATION
138.000 VOLT TRANSMISSION
SUBSTATION FROM TRANSMISSION LINE
INDUSTRIAL CUSTOMER
FIRST VOLTAGE REDUCTION 69.000 VOLTS
13.800 VOLTS DISTRIBUTION
69.000 VOLTS LOW-VOLTAGE TRANSMISSION
SECOND VOLTAGE REDUCTION
POWER CENTER INDUSTRIAL PLANT
SUBSTATION FROM LOW-VOLTAGE TRANSMISSION
DISTRIBUTION SUBSTATION
COMMERCIAL OR INDUSTRIAL CUSTOMER
13.800 VOLTS DISTRIBUTION
DISTRIBUTION TRANSFORMER
120 / 240 VOLTS
COMMERCIAL CUSTOMER
RESIDENTIAL CUSTOMER
SUBWAY VAULT

Figure 1. Electrical Service From the Generator to the Customer.

formers raise this voltage to 138,000 volts for transmission to distribution points.

Circuit power is the product of circuit current and voltage. Power loss — due to the resistance of the wires carrying the current — increases with the square of the current. Thus, losses may be reduced by transmitting the same power at a higher voltage and lower current. Some long transmission systems have voltages of 220,000 V and 330,000 V. Transformers are used to increase or decrease voltage throughout the system as needed.

Some large industrial customers may receive power directly from the transmission lines through their own substations. In most cases, a transmission substation keeps the voltage down to 69,000 V for distribution to local load areas. Many industrial customers are served by individual substations from low-voltage transmission lines. Distribution substations reduce the voltage further to 13,800 V for local distribution. These distribution lines serve smaller industrial and commercial customers and residential customers. Distribution transformers reduce the voltage to either 120 or 240 volts for smaller customers.

The term "transmission" is applied to those sections of the system that operate above 13,800 V. Distribution sections of the system operate at 13,800 V or below. Most industrial distribution systems (in plant) have voltages between 600 and 13,800 V. Commercial and residential distribution is at 120 and 240 V.

ENERGY LOSSES IN ELECTRICAL POWER SYSTEMS

Sources of loss in the distribution system include the resistance of the wires and switch contacts, hysteresis (magnetic) losses in transformers, and some radiated power. Even when components are designed for most efficient operation, some losses occur, since loss is dependent upon the system's current. Lower current produces less loss and higher efficiencies. In all cases, it is best to deliver necessary power at the lowest current — and, thus, the highest voltage — that is practical.

Transformers, electric motors, and transmission lines all have some inductance. Unless corrective measures are taken, the distribution system behaves as a series RL circuit, with the current wave lagging behind the voltage wave. Greater amounts of lag require larger currents to supply the same power at the load, resulting in larger losses. The amount of lag is indicated by the power factor described later in this module. Capacitors are used to correct the power factor by bringing current and voltage back into phase.

VOLTAGE CONTROL IN ELECTRICAL POWER SYSTEMS

Voltage delivered to the customer varies with the load. When little current flows, voltage drop along the transmission lines is small; the customer receives almost the full rated voltage of the system. When current is high, the voltage drop along the lines is greater; the customer experiences a voltage drop. Since electrically-operated devices are designed to be most efficient at their rated voltage, voltage drop reduces the efficiency of the customer's installation.

One method of regulating voltage delivered to the customer is the use of voltage regulator transformers. These transformers have output taps that provide a range of voltages. When current increase reduces the output voltage, voltage regulator transformers automatically change to a higher voltage tap to compensate. Another method that may be used at the end of long transmission lines is to install a series capacitor to correct the power factor and boost delivered voltage.

The remainder of this module discusses the power factor of an a.c. power system and the use of capacitors to increase efficiency and reduce voltage drop.

REVIEW OF A.C. CIRCUIT ANALYSIS

The current flow through an a.c. circuit with a constant voltage is dependent upon the impedance of the circuit as given by Equation 1.

$$I = \frac{E}{Z} \qquad \text{Equation 1}$$

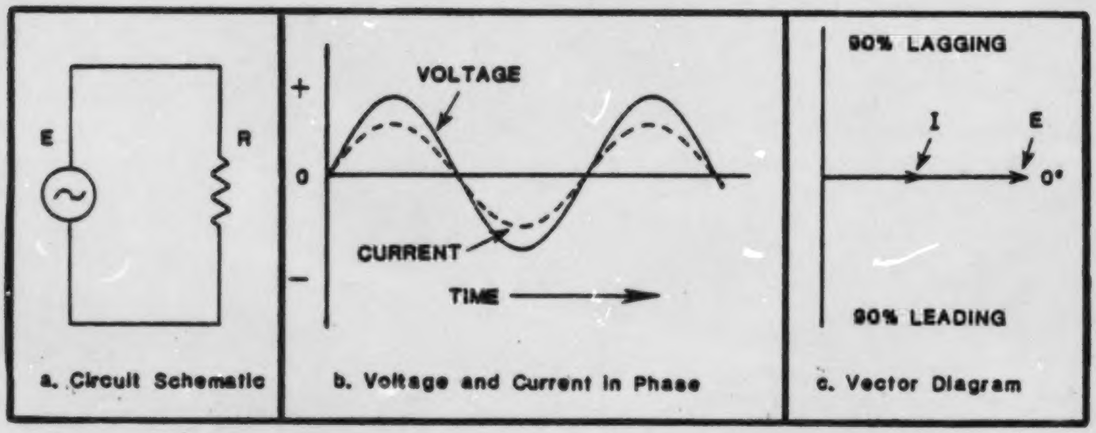
where:

I = Current, in amperes (A)
E = Voltage, in volts (root-mean-square, [rms])
Z = Impedance, in ohms (Ω)

The impedance of an a.c. circuit is composed of three elements: resistance, inductive reactance, and capacitive reactance.

A.C. CIRCUIT ELEMENTS

Figure 2a shows an a.c. circuit with a purely resistive load. The voltage and current are in phase, as shown in Figure 2b. Figure 2c is a vector diagram showing the current and voltage of this circuit. Resistance heaters and incandescent lights are purely resistive loads. The impedance of a resistive circuit is equal to the resistance. Equation 1 may be used to relate voltage, impedance, and current – as illustrated in Example A.



a. Circuit Schematic b. Voltage and Current In Phase c. Vector Diagram

Figure 2. Resistance in an A.C. Circuit.

EXAMPLE A: CURRENT IN A RESISTIVE CIRCUIT.

Given: In Figure 2, the applied voltage is 115 V and the resistance is 10Ω.

Find: Current

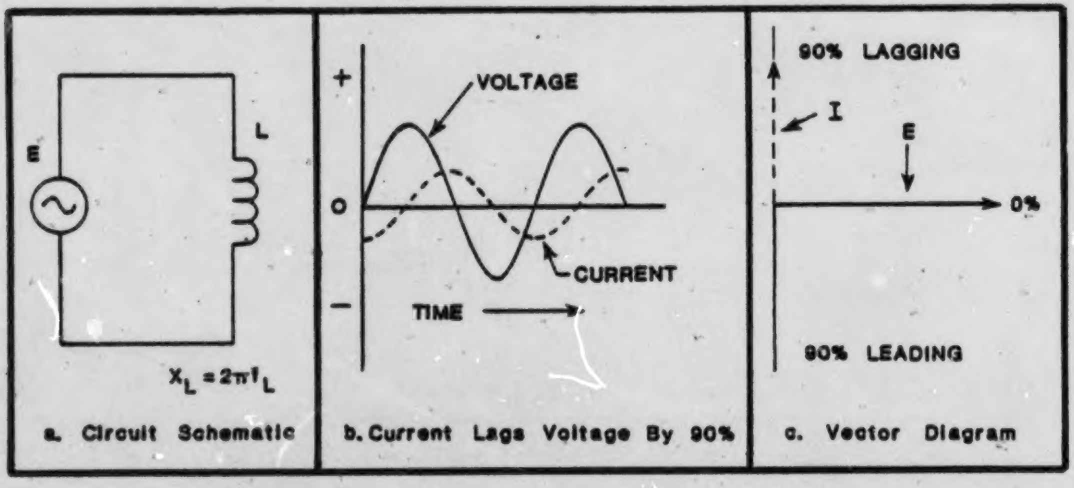
Solution:

$$I = \frac{E}{Z} \qquad (Z = R)$$

$$= \frac{115\ \text{V}}{10\Omega}$$

$$= 11.5\ \text{A.}$$

In an inductor (Figure 3), the current lags behind the voltage by 90°. Inductance is associated with the storage of energy in magnetic fields. All devices employing magnetic fields have some inductance. The impedance of an inductor is called the inductive reactance and is given by Equation 2.



a. Circuit Schematic
b. Current Lags Voltage By 90%
c. Vector Diagram

Figure 3. Inductance in an A.C. Circuit.

$$X_L = 2\pi fL \qquad \text{Equation 2}$$

where:

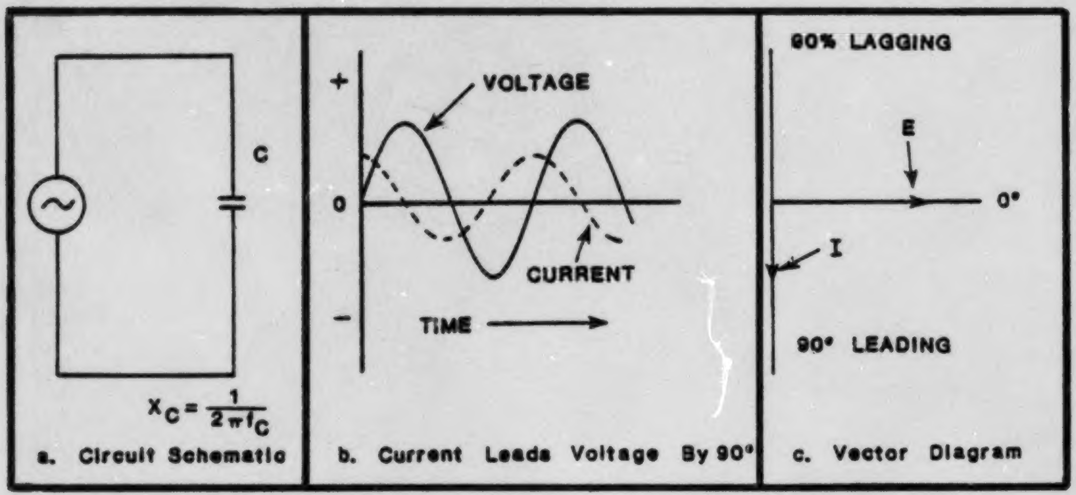
X_L = Inductive reactance
f = Frequency of a.c. wave
L = Inductance, in henrys

Example B shows the use of Equations 1 and 2 in determining the current in an inductive circuit.

EXAMPLE B: CURRENT IN AN INDUCTIVE CIRCUIT.	
Given:	In Figure 3, the applied voltage is 120 V, 60 Hz, and the inductance is 0.5 H (henry).
Find:	Current
Solution:	$X_L = 2\pi fL$ $= 2\pi(60)(0.5)$ $X_L = 188.5\Omega$ $I = \frac{E}{Z} \quad (Z = X_L)$ $= \frac{120\text{ V}}{188.5\Omega}$ $I = 0.637$ A.

There are no purely inductive circuits in practical applications. However, many common circuits contain a combination of inductance and resistance. These will be discussed later in this module.

Figure 4 shows a capacitive a.c. circuit in which the current leads the voltage by 90°. The impedance of a capacitor is given by Equation 3.


C
$X_C = \frac{1}{2\pi f_C}$
+
VOLTAGE
0
CURRENT
−
TIME
90% LAGGING
E
0°
I
90° LEADING

a. Circuit Schematic b. Current Leads Voltage By 90° c. Vector Diagram

Figure 4. Capacitance in an A.C. Circuit.

$$X_C = \frac{1}{2\pi fC} \qquad \text{Equation 3}$$

where:

X_C = Capacitive reactance
f = Frequency
C = Capacitance, in farads

Example C illustrates the use of Equations 1 and 3 to determine the current in a capacitive circuit.

EXAMPLE C: CURRENT IN A CAPACITIVE CIRCUIT.

Given: In Figure 4, the applied voltage is 110 V, 60 Hz, and the capacitance is 500 µf (microfarads).

Find: Current

Solution:

$$X_C = \frac{1}{2\pi fC}$$

$$= \frac{1}{2\pi\ (60)(500 \times 10^{-6})}$$

$$= \frac{1}{0.1885}$$

$$X_C = 5.3\Omega$$

$$I = \frac{E}{Z} \qquad (Z = X_C)$$

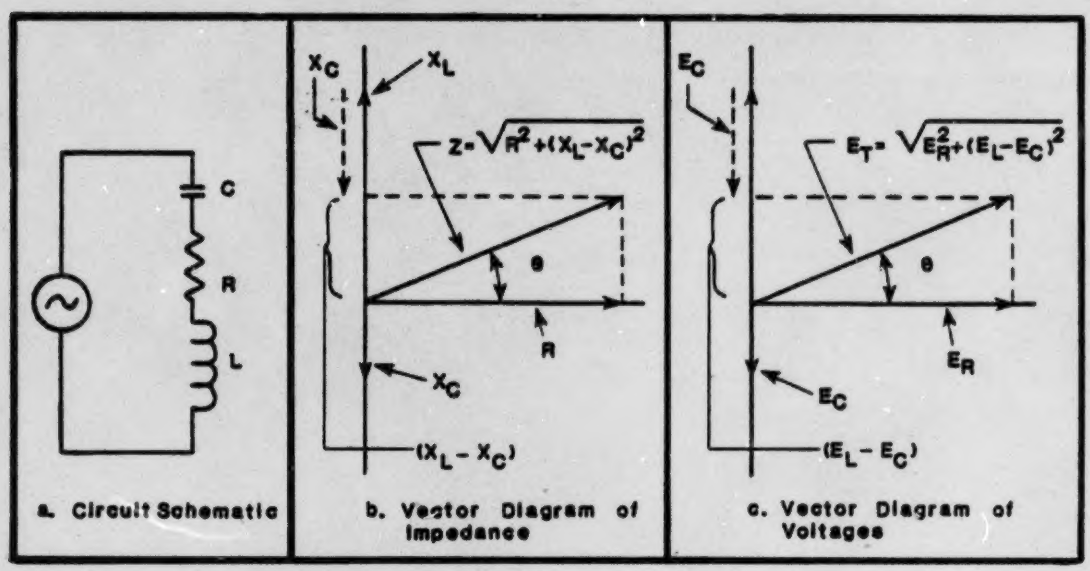
$$= \frac{110\ V}{5.3\Omega}$$

$$I = 20.7\ A.$$

There are few capacitive loads, but capacitors are routinely added to circuits to offset the effects of inductive loads. Although increasing the resistance or inductance of a circuit decreases current, increasing the capacitance increases current.

SERIES CIRCUITS

Figure 5a is the circuit schematic of a series circuit containing a resistor, inductor, and a capacitor. Since the same current flows through all three components, all currents must be in phase. Figure 5b is a vector diagram of this circuit. The total circuit impedance is given by Equation 4.


C
R
L
X_C
X_L
$Z = \sqrt{R^2 + (X_L - X_C)^2}$
θ
R
X_C
$(X_L - X_C)$
E_C
$E_T = \sqrt{E_R^2 + (E_L - E_C)^2}$
θ
E_R
E_C
$(E_L - E_C)$

a. Circuit Schematic

b. Vector Diagram of Impedance

c. Vector Diagram of Voltages

Figure 5. Series RLC Circuit.

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad \text{Equation 4}$$

Figure 5c is a vector diagram of voltages in the circuit. Voltages on the inductor and the capacitor are 180° out of phase with one another. If inductive reactance and capacitive reactance are equal, the two voltages cancel one another; the voltage and current of the source are in phase with the total voltage applied to the resistor. If inductive reactance and capacitive reactance are not equal, the phase angle between the current and voltage is given by Equation 5.

$$\text{COS}\ \theta = \frac{R}{Z} = \frac{E_R}{E_T} \qquad \text{Equation 5}$$

The relationships between the voltages in the circuit are given by Equation 6.

$$E_T = \sqrt{E_R{}^2 + (E_L - E_C)^2} \qquad \text{Equation 6}$$

Example D illustrates the use of Equations 4 and 5 to solve for the current and voltages of a series RL circuit.

EXAMPLE D: SERIES RL CIRCUIT.	
Given:	A series RL circuit has the following values: $E = 120$ V $R = 10\Omega$ $X_L = 4\Omega$
Find:	a. Circuit current b. Phase angle c. Voltage on each component

Example D. Continued.

Solution: a.

$$Z = \sqrt{R^2 + X_L{}^2} \quad \text{(Equation 4)}$$

$$= \sqrt{(10)^2 + (4)^2}$$

$$= \sqrt{116}$$

$$Z = 10.77\Omega$$

$$I = \frac{E}{Z} \quad \text{(Equation 1)}$$

$$= \frac{120\text{ V}}{10.77\Omega}$$

$$I = 11.14\text{ A.}$$

b.

$$\text{COS } \theta = \frac{R}{Z}$$

$$= \frac{10\Omega}{10.77\Omega}$$

$$\text{COS } \theta = 0.9285$$

$$\theta = \text{COS}^{-1}\ (0.9285)$$

$$\theta = 21.8°.$$

Current lags the voltage by 21.8°.

c. Voltage on each component may be determined using Equation 1:

Resistor	Inductor
$E_R = IR$	$E_L = IX_L$
$= (11.14\text{ A})(4\Omega)$	$= (11.14\text{ A})(4\Omega)$
$E_R = 111.4\text{ V.}$	$E_L = 44.56\text{ V.}$

Example D. Continued.

The problem may be checked by using Equation 5 for voltages.

$$E_T = \frac{E_R}{\cos\theta} \qquad \text{(Equation 5)}$$

$$= \frac{111.4\ V}{0.9285}$$

$$E_T = 120\ V.$$ Problem checks.

Equation 6 may also be used to check the problem.

$$E_T = \sqrt{E_R{}^2 + (E_L - E_C)^2} \qquad \text{(Equation 6)}$$

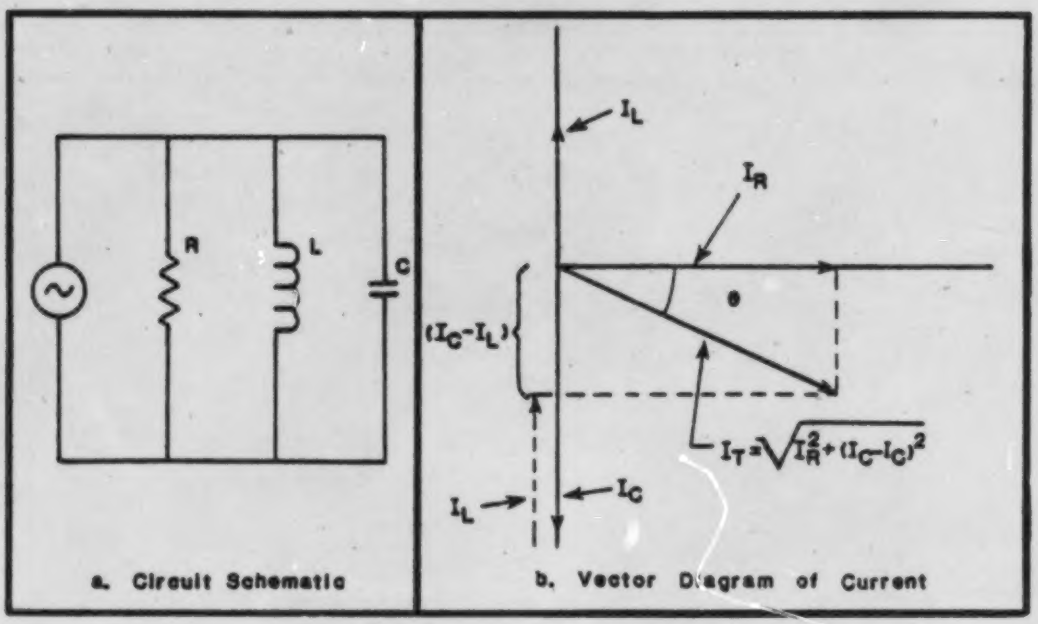
$$= \sqrt{(111.4)^2 + (44.56)^2}$$

$$= \sqrt{14,396}$$

$$E_T = 120\ V.$$ Problem checks.

PARALLEL CIRCUIT

Figure 6a is the schematic diagram of a parallel RLC circuit. In this circuit, the same voltage is applied to all components. Voltages for all are in phase. Currents are out of phase, as shown in Figure 6b. If inductive reactance and capacitive reactance are equal, currents are of equal magnitude. Since inductive reactance and capacitive reactance are 180° out of phase, they cancel each other, and the source current is that required by the resistor only.


R
L
C
I_L
I_R
θ
$(I_C - I_L)$
$I_T = \sqrt{I_R^2 + (I_C - I_C)^2}$
I_L
I_C

a. Circuit Schematic

b. Vector Diagram of Current

Figure 6. Parallel RLC Circuit.

The relationships between the currents of the parallel circuit are given by Equation 7.

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2} \qquad \text{Equation 7}$$

Example E illustrates the use of Equation 7 in determining the current of a parallel RLC circuit.

EXAMPLE E: PARALLEL RLC CIRCUIT.

Given: A parallel RLC circuit has the following values:

$$E_T = 120\ \text{V}$$
$$R = 5\Omega$$
$$X_L = 20\Omega$$
$$X_C = 15\Omega$$

Find:
a. Current through each component
b. Total current
c. Circuit impedance

Solution: a. The current through each component is determined using Equation 1.

$$I_R = \frac{E}{R} = \frac{120\ \text{V}}{5\Omega} \qquad I_L = \frac{E}{X_L} = \frac{120\ \text{V}}{20\Omega} \qquad I_C = \frac{E}{X_C} = \frac{120\ \text{V}}{15\Omega}$$

$$I_R = 24\ \text{A.} \qquad I_L = 6\ \text{A.} \qquad I_C = 8\ \text{A.}$$

b.

$$\begin{aligned} I_T &= \sqrt{I_R^2 + (I_L - I_C)^2} \\ &= \sqrt{(24)^2 + (6 - 8)^2} \\ &= \sqrt{580} \\ I_T &= 24.08\ \text{A.} \end{aligned}$$

c. Find total impedance using Equation 1.

$$\begin{aligned} Z &= \frac{E}{I} \\ &= \frac{120\ \text{V}}{24.08\ \text{A}} \\ Z &= 4.98\ \Omega. \end{aligned}$$

POWER FACTOR AND SYSTEM EFFICIENCY

The power factor is the ratio of the average (or active) power to the apparent power (root-mean-square voltage times root-mean-square current) of an alternating-current circuit.

POWER IN A.C. CIRCUITS

Power in a circuit is the product of current and voltage. Figure 7 shows the voltage, current, and power of a pure resistive a.c. circuit as functions of time. Since the current and voltage are in phase, power is always positive. The area under the power curve represents the energy transferred to the resistor.

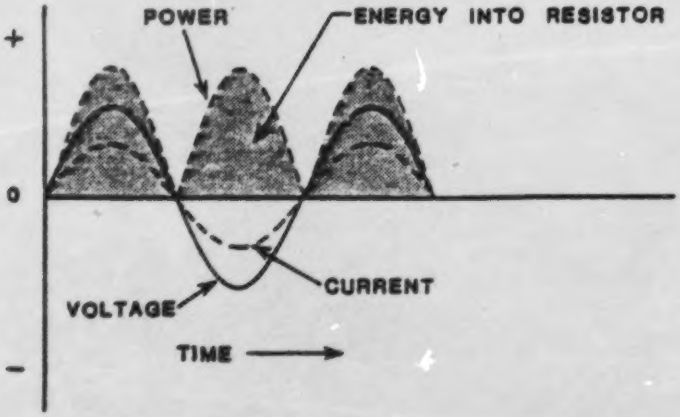


Figure 7. Power in a Resistive Circuit.

Figure 8 is a similar diagram for a pure inductive circuit. When current and voltage are both positive or both negative, power is positive and energy flows into the inductor, establishing a magnetic field. When one of these quantities is positive and the other is negative, energy flows from the inductor back into the power lines, decreasing the magnetic field. Although current is flowing through the inductor, no net power is transferred to the inductor. The same is true of pure capacitive circuits.

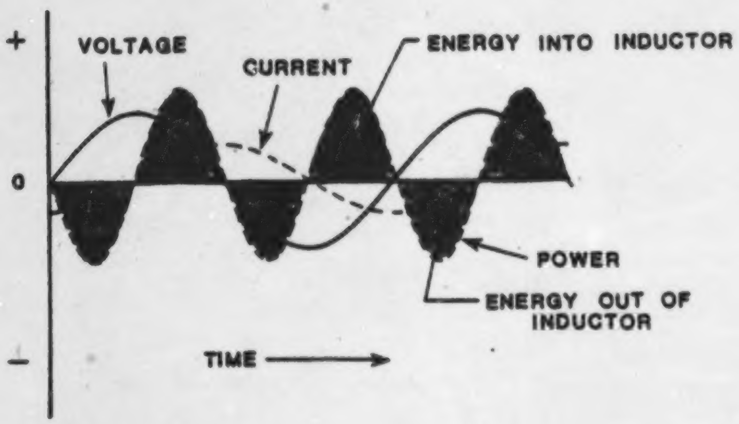


Figure 8. Power in an Inductive Circuit.

Most a.c. circuits include both resistance and inductance in series. Both electric motors and fluorescent light behave electrically as series RL circuits. Figure 9 shows the voltage, current, and power in such a circuit. The true power in the circuit is the power of the resistor. The power resulting from the energy flow into and out of the inductor is called reactive power and accomplishes no work. This power increases current flow through the conductors of the system and, thus, increases losses and voltage drop.

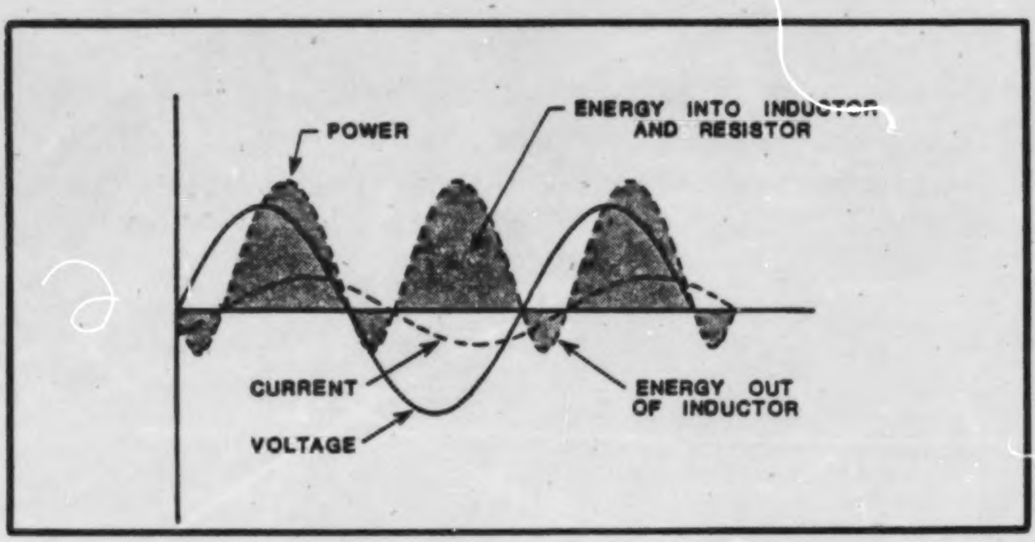


Figure 9. Power in a Series RL Circuit.

POWER FACTOR

The apparent power of a circuit is the product of the circuit voltage and amperage. Figure 10 shows the relationship between apparent power, true power, and reactive power.

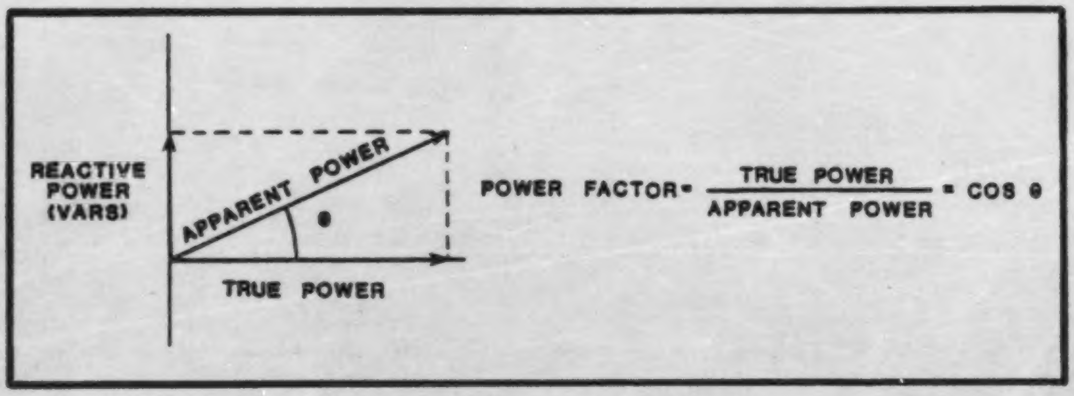

REACTIVE POWER (VARS)
APPARENT POWER
θ
TRUE POWER
POWER FACTOR = TRUE POWER / APPARENT POWER = COS θ

Figure 10. Power Factor.

The angle θ is the phase angle between the current and voltage in the circuit. The power factor is defined as the ratio of true power to apparent power and is equal to the cosine of the phase angle. If the voltage, current, and power factor of a circuit are known, the true power may be calculated using Equation 8.

$$TP = E \times I \times PF \qquad \text{Equation 8}$$

where:

TP = True power
PF = Power factor

Example F illustrates the use of Equation 8 to determine true power.

EXAMPLE F: POWER OF A MOTOR.	
Given:	A 5-hp electric motor operates at 220 V with a current of 19.3 A and a power factor of 0.09. The wires carrying current to the motor have a total resistance of 0.5Ω.
Find:	a. Apparent power b. True power of motor c. Voltage drop in power lines d. Loss in power lines

Example F. Continued.

Solution: a. Apparent power ... AP = EI
= (220 V)(19.3 A)
AP = 4,246 VA.

b. True power ... TP = EI (PF)
= (220 V)(19.3 A)(0.9)
TP = 3,821.4 W.

c. Voltage drop in lines ...
E = IR
= (19.3 A)(0.5Ω)
E = 9.65 V.

There will be a voltage drop of 9.65 V in the power line. To deliver 220 V at the motor, the source must have a voltage of approximately 230 V.

d. Loss in lines ...
$P = I^2R$
$= (19.3\ \text{A})^2(0.5)$
P = 186.2 W.

IMPROVING POWER FACTOR WITH SHUNT CAPACITORS

A power factor of 1.0 is the most efficient for an a.c. power distribution system because it produces the minimum line current. Figure 11 shows the most common method of correcting the power factor of an a.c. circuit. A shunt capacitor is added just before the RL load, as shown in

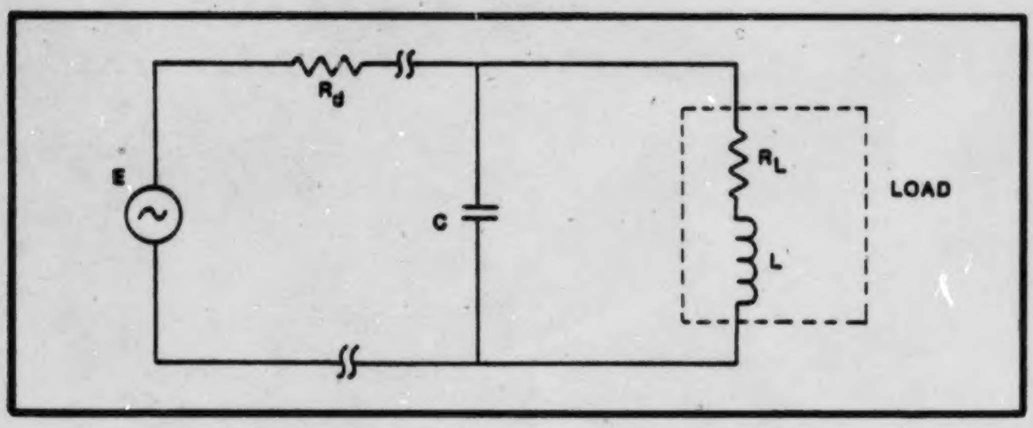


Figure 11. Power Factor Correction by a Shunt Capacitor.

Figure 11. This will not greatly change the current through the load, but will reduce the current through the distribution lines and the resulting voltage drop. Example G illustrates correction of power factor using a shunt capacitor to provide reactive power to offset that of the inductor.

EXAMPLE G: CORRECTION OF POWER FACTOR WITH A SHUNT CAPACITOR.

Given:	The load in Figure 11 is the motor of Example F with an operating voltage of 220 V, a current 19.3 A, and a power factor of 0.9. The resistance of the distribution system (Rd) is 0.5Ω.
Find:	a. Value of capacitor to give a power factor of 1.0 b. Voltage drop in power lines c. Loss in power lines

Example G. Continued.

Solution: a. Capacitance (from Figure 10) ...

$$RP = AP^2 - TP^2$$

$$= (4{,}246) - (3{,}821.4) \quad \text{(from Example F)}$$

$$= 3{,}425{,}418$$

$$RP = 1{,}851 \text{ VAR} \quad \text{(Volt-Amps Reactive).}$$

The shunt capacitor must supply a reactive power of 1,851 VAR.

The reactive power of the capacitor is given by ...

$$RP = I_C E_C$$

Thus, the capacitor current must be ...

$$I_C = \frac{RP}{E_C}$$

$$= \frac{1{,}851 \text{ VAR}}{220 \text{ V}}$$

$$I_C = 8.41 \text{ A.}$$

The capacitive reactance is then ...

$$X_C = \frac{E_C}{I_C}$$

$$= \frac{220 \text{ V}}{8.41 \text{ A}}$$

$$X_C = 26.16\Omega$$

$$C = \frac{1}{2\pi f X_C}$$

$$= \frac{1}{2\pi\ (60)(26.16)}$$

$$= \frac{1}{9{,}862}$$

$$C = 101.4\ \mu\text{F.}$$

Example G. Continued.

A shunt capacitor of 101.4 μF will correct the power factor of the system to 1.0.

b. Voltage drop ...

With the power factor corrected, the delivery system must provide only enough current to produce the true power.

$$I = \frac{TP}{E\ (PF)}$$

$$= \frac{3{,}821.4\ \text{VA}}{(220)(1.0)}$$

$$I = 17.4\ \text{A.}$$

The voltage drop in distribution system is given by ...

$$E = IR$$

$$= (17.4\ \text{A})(0.5\Omega)$$

$$E = 8.70\ \text{V.}$$

c. Line loss ...

$$P = I^2R$$

$$= (17.4\ \text{A})^2(0.5\Omega)$$

$$P = 151.4\ \text{W.}$$

Compare the answers for parts b and c to the values obtained in Example F. Both voltage drop and power loss are reduced by the addition of the capacitor.

IMPROVING POWER FACTOR WITH SERIES CAPACITORS

The use of shunt capacitors is the most common method of correcting power factor. However, in some cases, it is desirable to improve the power factor and increase the delivered voltage. This is most often necessary at the end of long distribution lines carrying relatively small currents. Figure 12 shows a capacitor connected in series with an RL load to correct the power factor and increase the delivered voltage. Example H illustrates this method of power factor correction.

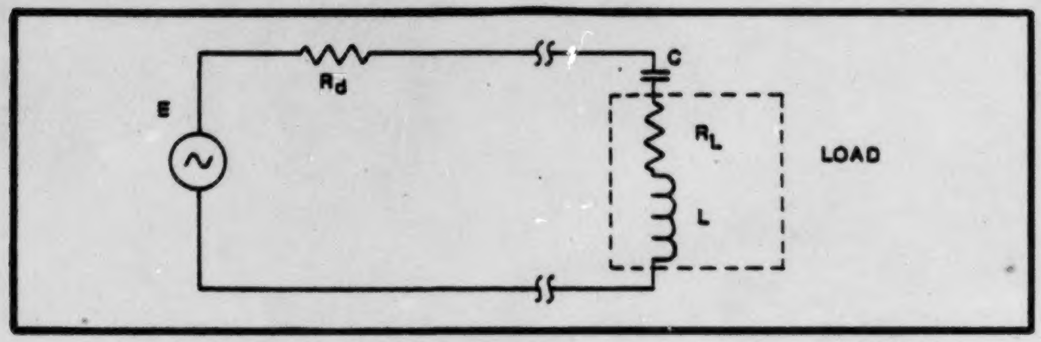


Figure 12. Power Factor Correction by a Series Capacitor.

EXAMPLE H: CORRECTION OF POWER FACTOR WITH A SERIES CAPACITOR.	
Given:	The motor from the previous example is operated at the end of a long power line with a resistance of Rd = 1.5Ω. Motor specifications are ... E = 220 V, I = 19.3 A, PF = 0.9, TP = 3,821 W, AP = 4,246 VA, RP = 1,841 VAR. Because of the voltage drop in the lines, only 200 volts are available at the site of the motor.

Example H. Continued.

Find: a. Series capacitance to give a power factor of 1.0

b. Voltage at motor terminals with capacitor in place

Solution: a. Capacitance ...

In a series RLC circuit, the power factor is 1.0 when $X_C = X_L$. Determine the value of X_L.

The reactive power of an inductor is given by ...

$$RP = I_L \; E_L$$

Thus ...

$$E_L = \frac{RP}{I_L}$$

$$= \frac{1{,}851 \text{ VAR}}{19.3 \text{ A}}$$

$$E_L = 95.9 \text{ V.}$$

During normal operation, the inductor voltage is 95.9 V.

$$X_L = \frac{E_L}{I_L}$$

$$= \frac{95.9 \text{ V}}{19.3 \text{ A}}$$

$$X_L = 4.97\Omega.$$

The capacitive reactance should then be 4.97Ω.

$$C = \frac{1}{2\pi f X_C}$$

$$= \frac{1}{2\pi \; (60)(4.97\Omega)}$$

$$C = 534 \; \mu\text{F.}$$

Example H. Continued.

b. Voltage at motor terminals ...
The true power of the resistance load is given by ...

$$TP = I_R \, E_R$$

Thus, during normal operation ...

$$E_R = \frac{TP}{I_R}$$

$$= \frac{3{,}821 \text{ VA}}{19.3 \text{ A}}$$

$$E_R = 198 \text{ V}.$$

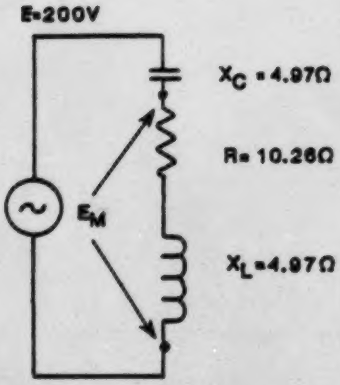
The resistance is then ...

$$R = \frac{E_R}{I_R}$$

$$= \frac{198 \text{ V}}{19.3 \text{ A}}$$

$$R = 10.26\Omega.$$

The circuit with the capacitor in series may be represented by the diagram at the right with a source voltage of 200 V. The voltage delivered to the motor is the voltage (Vm) across the resistor and inductor in series (Em). Solve for Em.



Example H. Continued.

Circuit impedance ...

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad \text{(Equation 4)}$$

$$= \sqrt{(10.26)^2 + (4.97 - 4.97)^2}$$

$$Z = 10.26\Omega$$

$$I = \frac{E}{Z} \qquad \text{(Equation 1)}$$

$$= \frac{200\ \text{V}}{10.26\Omega}$$

$$I = 19.5\ \text{A.}$$

Calculate voltages on resistor and inductor.

$$E_R = IR \qquad\qquad E_L = I\,X_L$$

$$= (19.5\ \text{A})(10.26\Omega) \qquad\qquad = (19.5\ \text{A})(4.97\Omega)$$

$$E_R = 200\ \text{V.} \qquad\qquad E_L = 96.9\ \text{V.}$$

Determine Em.

$$Em = \sqrt{E_R{}^2 + E_L{}^2} \qquad \text{(Equation 6)}$$

$$= \sqrt{(200)^2 + (96.9)^2}$$

$$Em = 222\ \text{V.}$$

Adding a capacitor in series corrects the power factor and increases the voltage delivered to the RL part of the circuit. The motor has an applied voltage of 222 V, even though the total voltage across the RLC series circuit is only 200 V.

THREE-PHASE POWER

Electrical power generators produce three-phase power and all distribution is three-phase – except the final distribution circuits at 120 and 240 V. Three-phase power results in a more efficient distribution system and a smoother power delivery. Power factor correction of three-phase systems with capacitors requires three capacitors (or sets of capacitors) with one connection between each pair of phases – or with a connection in series with each phase.

Current in a three-phase system is the current flowing in one of the three conductors. Voltage is the phase-to-phase voltage. In this case, the true power is given by Equation 9.

$$P = 1.73\ IE\ (PF) \qquad \text{Equation 9}$$

where:

P = True power
I = Current, in amps
E = Voltage
PF = Power factor
1.73 = Constant

Example I illustrates the use of Equation 9.

EXAMPLE I: CURRENT OF A THREE-PHASE MOTOR.

Given: A 10-hp motor has an efficiency of 92% and a power factor of 0.9. It is operated on 220 V, 3-phase power at 85% of its rated load. (1 hp = 746 W)

Find: Current

Solution: First, determine the true power consumption of the motor.

$$P = (10\ \text{hp})\left(\frac{746\ \text{W}}{\text{hp}}\right)(0.85)$$

$$P = 6{,}341\ \text{W}$$

$$P = 1.73\ IE\ (PF) \qquad \text{(Equation 9)}$$

$$I = \frac{P}{(1.73)\ E\ (PF)}$$

$$= \frac{6{,}341}{(1.73)(220)(0.9)}$$

$$I = 18.5\ \text{A.}$$

SUMMARY

Electrical power distribution systems are RL circuits. Inductance is present in motors, generators, transformers, and in transmission lines. Inductance results in a lagging power factor.

The reactive power of the system does no work, but does increase current through the conductors of the distribution system. The power factor can be corrected to 1.0 for the minimum current (maximum efficiency) by including capacitors in the circuit near the load.

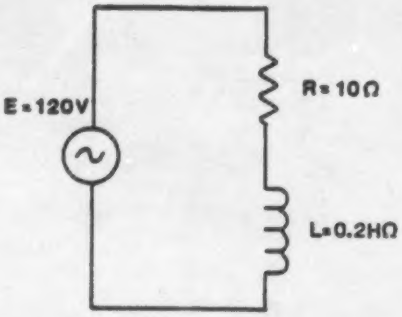
This reduces voltage drop in the power lines. The capacitor is chosen to provide the same reactive power as the inductance of the circuit. Power lines must then carry only the current necessary to deliver true power.

The capacitor is usually connected in parallel. However, series capacitors are used at the end of long lines to boost the voltage delivered to an inductive load.

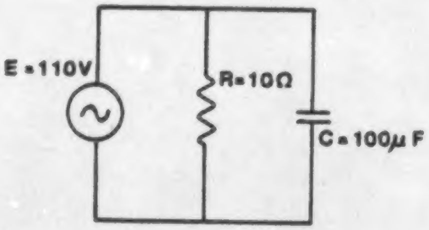
Power factor correction is an important technique in improving electrical system efficiency.

EXERCISES

1. A series RL circuit has a resistance of 10Ω, an inductance of 0.2 H and an applied voltage of 120 V. Find the following:
   a. Inductive reactance
   b. Impedance
   c. Current
   d. Voltage on resistor
   e. Voltage on inductor
   f. Phase angle
   g. Power factor
   h. True power
   i. Reactive power



2. A parallel RC circuit has a resistance of 10Ω, a capacitance of 100 μF, and an applied voltage of 110 V. Find the following:
   a. Capacitive reactance
   b. Current through resistor
   c. Current through capacitor
   d. Source current
   e. Circuit impedance
   f. Power factor



3. A single-phase motor has a power factor of 0.86, a current of 9.2 A and a voltage of 120 V. Determine the following:
   a. True power
   b. Reactive power
   c. Shunt capacitance for a power factor of 1.0
   d. Series capacitance for a power factor of 1.0
   e. Voltage applied to a motor with series capacitor in circuit

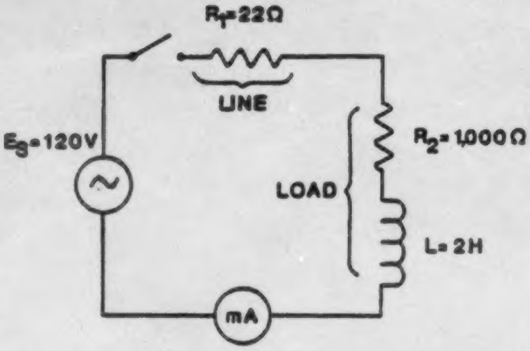
4. A three-phase motor rated at 5 hp operates on 230 V with a power factor of 0.92 and an efficiency of 87%. What current does the motor draw at full load?
5. A motor is rated at E = 120 V, I = 12.2 A, PF = 0.9. It is operated on a long distribution line with a source voltage of 120 V and a line resistance of 1.5Ω. Determine the following:
    a. Resistance of motor
    b. Voltage available at motor without power factor correction
    c. Series capacitance necessary for power factor correction
    d. Voltage available at motor with power factor correction

LABORATORY MATERIALS

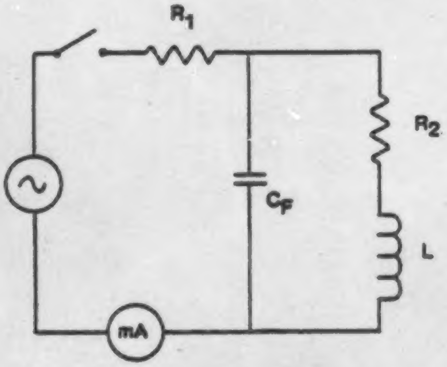
120 V a.c. outlet, with switch
22Ω, 1-W resistor
1,000Ω, 15-W resistor
2-H (henry) inductor, 120 mA (milliampere), maximum current
Several capacitors in the range of 1.0 μF to 5.5 μF,
120 V a.c.
VOM
A.C. milliammeter, 0-100 mA
Connecting wires

LABORATORY PROCEDURES

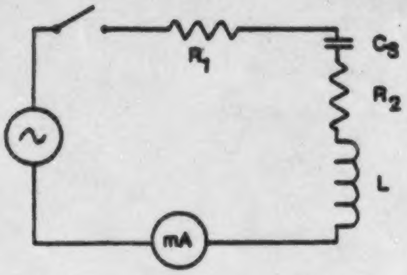
1. Connect the components as indicated at right. The 22Ω resistor will represent the resistance of the delivery system. The 1,000Ω resistor and 2-H inductor are the load.



2. Measure the resistance of the load (resistor and inductor in series) and record the value in Data Table 1.
3. Close the power switch and measure the voltage of the source, voltage on the load, voltage drop in the power line (22Ω resistor) and the current. Record these values in Data Table 1. Open the power switch.
4. Calculate the circuit parameters to complete the first section of Data Table 1. Calculate the value for the series capacitor for power factor correction as illustrated in Example H. Calculate the value for the parallel capacitor for power factor correction as illustrated in Example G.
5. With power removed from the circuit, select the proper capacitor for parallel connection to give a power factor of 1.0. Install it in the circuit as shown at right. Record the capacitance in Data Table 2.



6. Energize the circuit and measure voltage on the load, voltage drop in the line, and current. Record in Data Table 2. Open the power switch.
7. Complete Data Table 2 following the previous procedure.
8. With power removed from the circuit, select the proper capacitor for a series connection to give a power factor of 1.0. Install it in the circuit as shown at left. Record the capacitance in Data Table 3.



9. Energize the circuit. Measure and record the values specified in Data Table 3.
10. Disconnect the circuit. Complete this section of Data Table 3.
11. Complete Data Table 4 to compare losses in the three circuits.

DATA TABLES

DATA TABLE 1. RL CIRCUIT WITH NO POWER FACTOR CORRECTION.

MEASURED:

Resistance of load ... R_L = ______

Voltage of source ... E_S = ______

Voltage on load ... E_L = ______

Current ... I = ______

Voltage drop in line ... E_d = ______

CALCULATED:

Apparent power ... $AP = E_L\ I$ = ______

True power ... $TP = I^2\ R_L$ = ______

Reactive power ... $RP = \sqrt{AP^2 - TP^2}$ = ______

Power factor ... $PF = \frac{TP}{AP}$ = ______

Phase angle ... $\theta = \cos^{-1}(PF)$ = ______

VALUES FOR POWER FACTOR CORRECTION:

Series capacitor ... C_S = ______

Parallel capacitor ... C_P = ______

DATA TABLE 2. RL CIRCUIT WITH SHUNT CAPACITOR.

	Capacitance:	C_P =	________
MEASURED:	Voltage on load ...	E_L =	________
	Voltage drop in line ...	E_d =	________
	Current ...	I =	________
CALCULATED:	Apparent power ...	AP =	________
	True power ...	TP =	________
	Reactive power ...	RP =	________
	Power factor ...	PF =	________
	Phase angle ...	θ =	________

DATA TABLE 3. RL CIRCUIT WITH SERIES CAPACITOR.

	Capacitance:	C_S =	________
MEASURED:	Voltage on load ...	E_L =	________
	Voltage drop on line ...	E_d =	________
	Voltage on capacitor ...	E_C =	________
	Current ...	I =	________
CALCULATED:	Apparent power ...	AP =	________
	True power ...	TP =	________
	Reactive power ...	RP =	________
	Power factor ...	PF =	________
	Phase angle ...	θ =	________

DATA TABLE 4. COMPARISON OF CIRCUITS.

Circuit	True Power $_{(W)}$	Line Loss $P_L = IE_{d\,(W)}$	Total Power $TP + P_L$ (W)	% Loss $\frac{P_L}{TP + P_L} \times 100$
RL Circuit				
Parallel Capacitor				
Series Capacitor				

REFERENCES

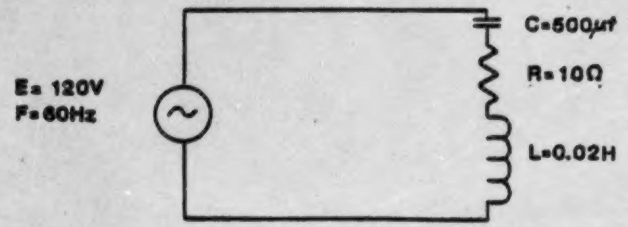
Commonwealth Edison Company. Power Plant Electrical Fundamentals. Books 1 and 2. Commonwealth Edison Co., 1979.

Pansini, Anthony J. Basic Electrical Power Distribution, Volume I. Rochelle Park, NJ: Hayden Book Co., 1971.

TEST

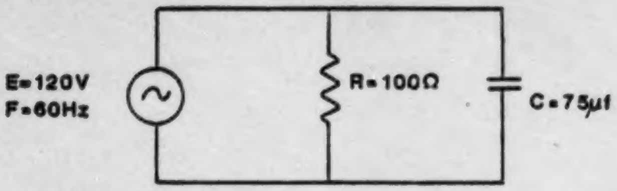
Please circle the appropriate answer.

1. In the circuit at the right, the voltage on the inductor is ...


E= 120V
F=60Hz
C=500μf
R=10Ω
L=0.02H

   a. 120 V.
   b. 117 V.
   c. 88.3 V.
   d. 62.2 V.
   e. 41.6 V.

2. In the circuit at the right, the total current is ...


E=120V
F=60Hz
R=100Ω
C=75μf

   a. 1.2 A.
   b. 3.4 A.
   c. 4.6 A.
   d. 3.6 A.
   e. 2.2 A.

3. A single-phase motor with an efficiency of 86% delivers a power of 2.63 hp (1 hp = 746 W) when operated at 225 V with a current of 11.5 A. Determine the power factor.
   a. 0.88
   b. 0.65
   c. 1.14
   d. 0.85
   e. 0.94

4. A three-phase motor has phase-to-phase voltage of 440 V and a current of 132 A. It has an efficiency of 91% and a power factor of 0.89. Find the output horsepower.
   a. 119 hp
   b. 78 hp
   c. 80 hp
   d. 76 hp
   e. 109 hp

5. A motor has an apparent power of 4 kW and a power factor of 0.9. Find the reactive power.
   a. 3,600 W
   b. 400 W
   c. 1,744 W
   d. 1,432 W
   e. 0

6. A single-phase motor operating at 120 V with a current of 17 A has a power factor of 0.91. What value of shunt capacitor will correct the power factor to 1.0?
   a. 550 μF
   b. 1,560 μF
   c. 15.6 μF
   d. 5.5 μF
   e. 1.67 μF

7. The same motor in problem 6 is installed with a series capacitor to correct the power factor. The value of the series capacitor is ...
   a. 380 μF.
   b. 905 μF.
   c. 38 μF.
   d. 90.5 μF.
   e. 1,560 μF.

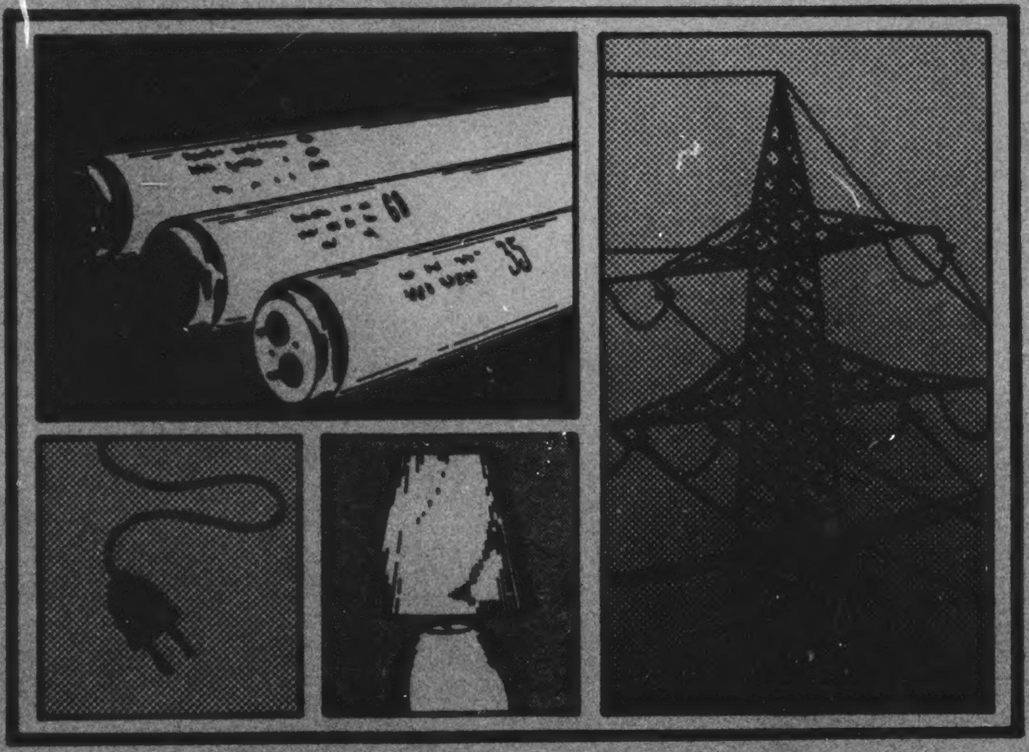
8. Using a series capacitor for power factor correction will ...
   a. increase delivered voltage.
   b. increase line current.
   c. increase power loss in transmission lines.
   d. increase efficiency of power delivery system.
   e. All of the above are correct.
   f. Only a, b, and d are true; c is false.

9. Using a parallel capacitor for power factor correction will ...
   a. increase line current.
   b. decrease power loss in transmission lines.
   c. reduce voltage drop.
   d. All of the above are correct.
   e. Only b and c are true; a is false.
   f. Only a and b are true; c is false.

10. In most practical applications, power factor correction is ...
   a. an unprofitable waste of time.
   b. accomplished by shunt capacitors.
   c. accomplished by series capacitors.
   d. unnecessary as inductive and capacitive loads in most systems tend to balance.

ENERGY TECHNOLOGY
CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-02
ELECTRICAL POWER TRANSMISSION AND DISTRIBUTION

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Electrical power is such a common convenience in this country that most people never think about what is required to deliver power to the customer. Electrical power transmission and distribution systems are complex and sophisticated networks. Networks spread throughout the area served and interconnect to other areas, providing reliable power at proper voltages and the highest efficiency possible.

PI-02, "Electrical Power Transmission and Distribution," describes the major components of transmission and distribution systems — including transmission lines, transformers, circuit breakers, switches, voltage regulators, and controls. It is not the intent of this module to provide a detailed description of the entire system or its operation. Hundreds of books have been written on the subject and new ones are published continuously. Since the electrical power industry is in a continual state of development as new products and procedures become available, current information on the state of the art may be found in a variety of specialized periodicals.

This module is intended to introduce the student to the basic components and practices that are common throughout the industry and to prepare the student for a more detailed description of the equipment used in industrial, commercial, and residential settings.

The laboratory section of this module consists of a field trip, to one or more substations, where the student will observe the equipment described.

PREREQUISITES

The student should have completed Module PI-01, "Efficiency of Electrical Distribution Systems."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Sketch a diagram of an electrical power transmission and distribution system – including generating stations, switching stations, distribution substations, tie lines to other utilities, and distribution circuits. State the approximate voltages present in each portion of the system.
2. Sketch, describe, and explain the function of the following system components:
   a. Lightning arresters
   b. Transformers
   c. Voltage regulators
   d. Oil circuit breakers
   e. Airblast circuit breakers
   f. Gas circuit breakers
   g. Disconnect switches
   h. Motor-operated disconnects
   i. Voltage transformers
   j. Current transformers
3. Explain the factors resulting in a leading or lagging power factor in the distribution system and the methods used to correct the power factor at the substations.

4. Describe the construction of the towers and cables used for electrical power transmission.
5. Given a schematic of a substation, identify the symbols for the major components — including transformers, circuit breakers, switches, and voltage regulators.
6. Visit a substation and identify and sketch the components. Describe the operation of the station.

TYPICAL TRANSMISSION AND DISTRIBUTION SYSTEM

Figure 1 is a diagram of a typical electrical power transmission and distribution system. This particular system contains three generating stations, each producing an electrical power at 20,000 V. This voltage is raised to 138,000 V for transmission. At switching substations, this voltage is reduced to 69,000 V for transmission to distribution substations.

In some cases, subtransmission voltages of 35,000 V may also be used. The actual voltages used in any system, or in any part of a system, depend upon the distance the power is to be transmitted, geographical considerations, climatic conditions, and government regulations. Distribution substations further reduce the voltage to 13,800 V for distribution to customers.

The figure also shows a tie line to an adjacent utility. Electrical power systems are not isolated, but are connected in a power grid that covers the country. The lines connecting these systems together are usually operated at high voltages because of the long distances involved. Some extra high voltage (ehv) lines operate at voltages or 735 kV. These lines are used to supply power from adjacent companies when the local utility cannot meet demands. Utilities usually do not like to take power from these tie lines unless the power has been contracted for in advance; rates are higher on a short-notice basis.

However, in some cases, substantial amounts of power are delivered by these lines on a routine basis. Often,

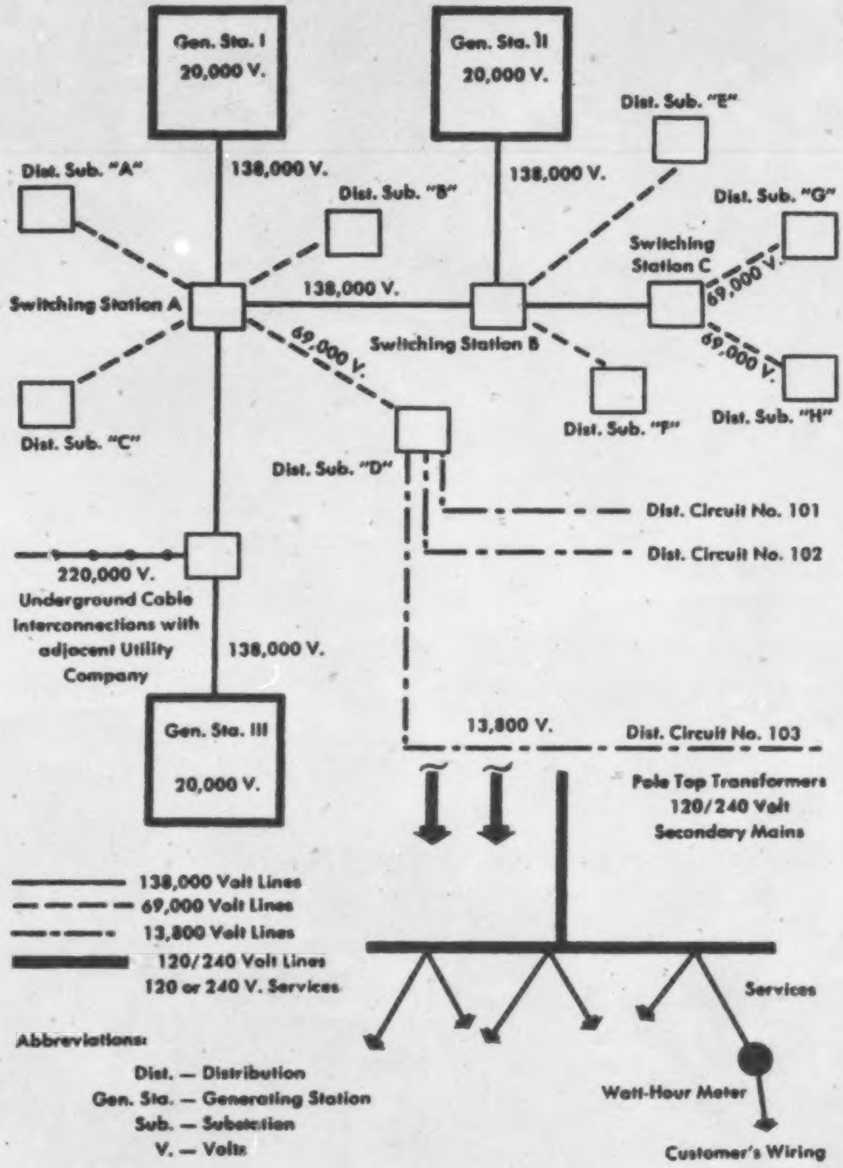

Gen. Sta. I
20,000 V.
Gen. Sta. II
20,000 V.
Dist. Sub. "E"
Dist. Sub. "A"
138,000 V.
Dist. Sub. "B"
138,000 V.
Dist. Sub. "G"
Switching Station C
69,000 V.
138,000 V.
Switching Station A
Switching Station B
69,000 V.
69,000 V.
Dist. Sub. "C"
Dist. Sub. "F"
Dist. Sub. "H"
Dist. Sub. "D"
Dist. Circuit No. 101
Dist. Circuit No. 102
220,000 V.
Underground Cable Interconnections with adjacent Utility Company
138,000 V.
Gen. Sta. III
20,000 V.
13,800 V.
Dist. Circuit No. 103
Pole Top Transformers
120/240 Volt
Secondary Mains
138,000 Volt Lines
69,000 Volt Lines
13,800 Volt Lines
120/240 Volt Lines
120 or 240 V. Services
Services
Abbreviations:
Dist. — Distribution
Gen. Sta. — Generating Station
Sub. — Substation
V. — Volts
Watt-Hour Meter
Customer's Wiring

Figure 1. Diagram of a Typical Transmission and Distribution System.

utilities purchase large amounts of power from companies that are large distances away. This power may be transmitted over the lines of several companies that are located between the producer of the power and the user. California, for example, uses large amounts of power generated by abundant hydroelectric sources in Washington and British Columbia. In other cases, such lines are run for hundreds of miles from power plants at coal mining sites to cities. High voltage tie lines may also be used to bring power to an area when the local system has experienced a generator failure.

The electrical power transmission and distribution system of this country is actually one large interlocking grid made up of many individual utilities. The power is directed through the system by switching stations and distribution substations. This module will describe the major system components used to transmit and control that power.

TRANSMISSION LINES

Transmission lines may be either overhead or underground. Overhead lines are more common because of lower construction cost and higher efficiency. However, in high population areas and for many lower voltage distribution systems, underground lines are popular. This discussion will deal with overhead lines only. Underground cables will be discussed briefly in Module PI-03, "Industrial Electrical Distribution."

POLES AND TOWERS

Overhead power lines may be supported by poles made of wood, steel, or concrete, or by structural steel towers. Wooden poles are used mainly for local distribution systems, but some older transmission lines have wooden poles. Newer transmission lines use structural steel towers or steel poles almost exclusively. Figure 2 shows several types of steel poles and towers that are in common use. These structures

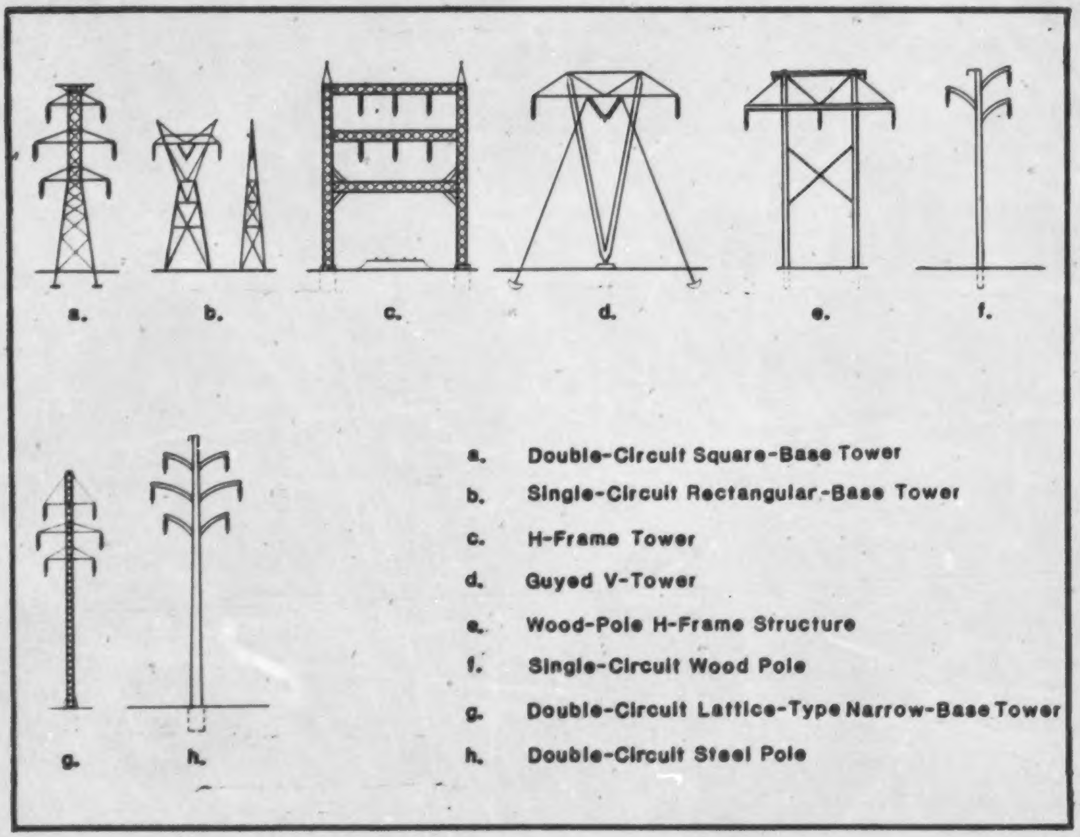

a.
b.
c.
d.
e.
f.
g.
h.
a. Double-Circuit Square-Base Tower
b. Single-Circuit Rectangular-Base Tower
c. H-Frame Tower
d. Guyed V-Tower
e. Wood-Pole H-Frame Structure
f. Single-Circuit Wood Pole
g. Double-Circuit Lattice-Type Narrow-Base Tower
h. Double-Circuit Steel Pole

Figure 2. Types of Poles and Towers.

carry either one or two three-phase circuits; that is, either three or six conducting cables. These cables are arranged to produce the minimum power loss due to corona. Cables are spaced far enough apart to reduce capacitance between the cables and to prevent arcing. A grounded shield wire is strung at the top of the structure above power lines to divert lightning strikes to the ground.

CABLES

Most transmission cables are made of standard aluminum and have a steel core. Steel provides strength to support the weight of the cable; aluminum provides good electrical conduction. Copper is a better conductor than aluminum, but copper is more expensive and heavier and is seldom used for transmission. Cables are not insulated and depend upon the air gap for electrical isolation. Cables are attached to the tower by ceramic insulators.

LIGHTNING ARRESTERS

Lightning strikes are a common occurrence on many power lines and circuit components must be protected from the high voltages and currents produced by such strikes. Figure 3 shows a valve lightning arrester. This device consists of a series of spark gaps and a resistor called the valve element. The top terminal of the arrester is connected to the power line; the bottom terminal is connected to ground. Line voltage is insufficient to ionize the air in the gaps,

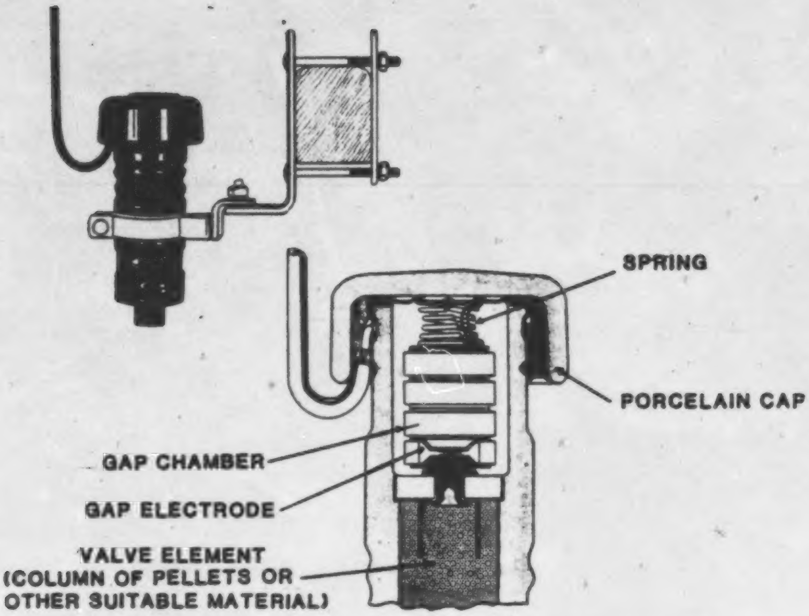

SPRING
PORCELAIN CAP
GAP CHAMBER
GAP ELECTRODE
VALVE ELEMENT
(COLUMN OF PELLETS OR
OTHER SUITABLE MATERIAL)

Figure 3. Lightning Arresters.

but a lightning strike breaks down the air and is transmitted to the ground through the resistor element. When the surge is over, the resistor reduced current to the level that arcs are extinguished and no line energy is lost. Lightning arresters are used on all transmission and distribution lines in areas where lightning poses a problem and are usually installed at substations and distribution transformers.

SUBSTATIONS

Control of the transmission and distribution system is applied at switching stations and substations. In some systems, all substations are controlled from a central dispatcher location by means of radio frequency signals carried on the power lines. In other systems, only parts are controlled from a central location, with some parts under local control or operated automatically. In all cases, the function of substations is essentially the same. Substations perform the following functions:

- Switching networks direct power from incoming lines to several feeder lines that carry power to other parts of the system.
- Transformers reduce the voltage for distribution or increase it for transmission to other areas.
- Tie lines connect one utility to another at high voltage bulk stations.
- Switches may be used to de-energize sections of the system for maintenance or repair.
- Metering devices monitor and record data that are essential for the proper and efficient operation of the system.

Substations normally include transformers, switches, voltage regulators, capacitors, or other devices for adjusting the power factor and measurement equipment. A battery bank is usually included for the operation of switching and monitoring equipment during periods when a.c. power is disconnected. The remainder of this module discusses components that are employed in substations for the control of the transmission and distribution system.

SYSTEM COMPONENTS

System components include transformers, voltage regulators, circuit breakers, disconnect switches, instrumentation, power factor correction, and protective relaying.

TRANSFORMERS

A wide variety of transformers are used throughout electrical power systems. Their size varies from large three-phase transformers for ehv transmission systems – that can handle thousands of megawatts – to 5 kVA single-phase distribution transformers. Figure 4 shows a typical three-phase transformer of a small distribution substation. Most power transformers have the same basic components and all perform the same function – to increase or decrease voltage. Only 30 years ago, transformers weighed about five pounds per kVA and had efficiencies of around 95%. Modern transformers weigh only one pound per kVA and have efficiencies of 99.5%. The secondaries of power transformers have several taps for adjustment of the output voltage. Typically, voltage may be changed in steps of about 2½% by changing taps. Such adjustments must be made with the transformer de-energized, as the tap changers are not designed to operate under load. A discussion of the theory of operation and the connection of transformers may be found in Electromechanical Devices, Module EM-03, "Transformers."

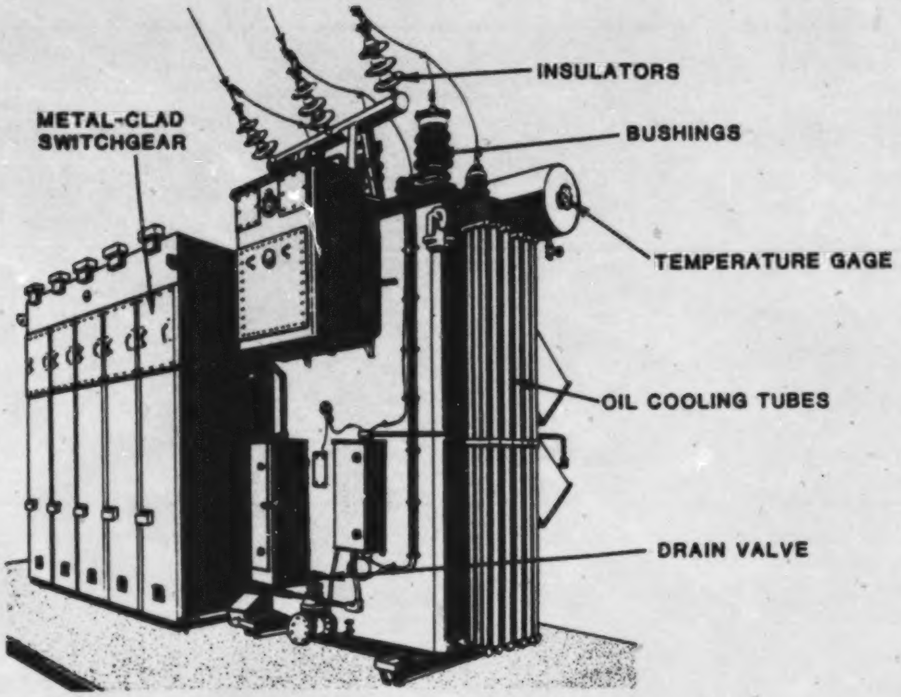

INSULATORS
METAL-CLAD SWITCHGEAR
BUSHINGS
TEMPERATURE GAGE
OIL COOLING TUBES
DRAIN VALVE

Figure 4. Substation Transformer.

VOLTAGE REGULATORS

Increasing the current through a transmission line results in an increased voltage drop across the line. In many cases, this increased drop is sufficient to reduce the delivered voltage to an undesirable value. A voltage regulator may be used to boost the voltage to the proper level and to reduce it later when the current demand drops. Figure 5 is a simplified schematic of a voltage regulator.

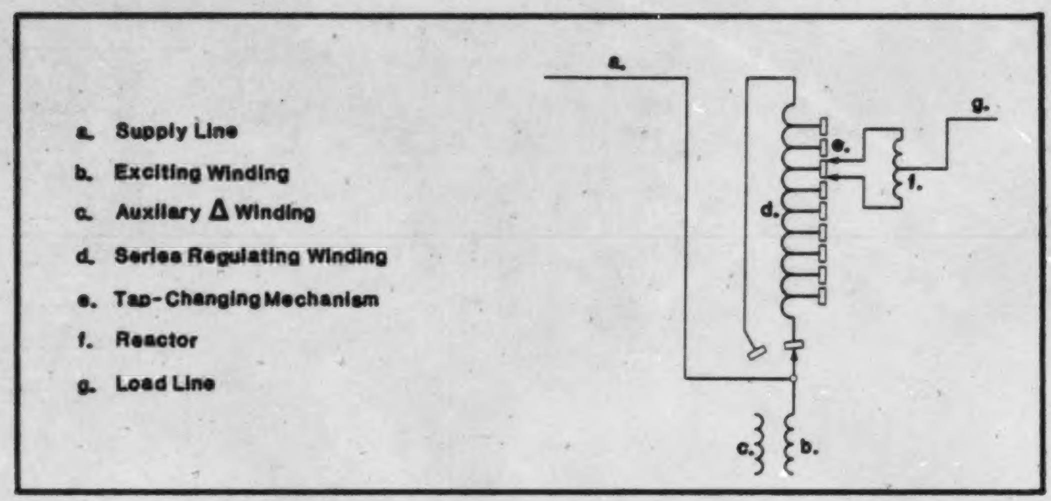

a. Supply Line
b. Exciting Winding
c. Auxiliary Δ Winding
d. Series Regulating Winding
e. Tap-Changing Mechanism
f. Reactor
g. Load Line
a.
g.
e.
f.
d.
c.
b.

Figure 5. One Phase of Single-Core Step-Voltage Regulator.

Only one phase of a three-phase regulator is shown. It is essentially a transformer with multiple taps and a tap changer that operates under load. One end of the exciting winding is connected to one phase of the incoming power. The other end of this winding is connected to the exciting winding of the other two phases to form a Y connection of the transformer.

The auxiliary Δ winding allows a third harmonic current to circulate in the transformer and increases its efficiency. The output is taken from the series, regulating winding by means of multiple taps. This voltage is added to the input voltage to produce the desired output.

A reversing switch may be used to change the polarity of the series winding, resulting in voltage subtraction if a voltage reduction is desired. The inductor in the tap-changing mechanism limits current flow through the portion of the series winding that is short-circuited during the changing of taps.

Voltage regulators are controlled automatically by a voltage transformer that senses the output voltage of the regulator. Figure 6 shows a typical substation voltage regulator. The appearance is very similar to that of an ordinary transformer. Voltage regulators of this type are used throughout the transmission and distribution systems, as needed. In many cases, voltage regulators are added to existing substations as power demand increases.

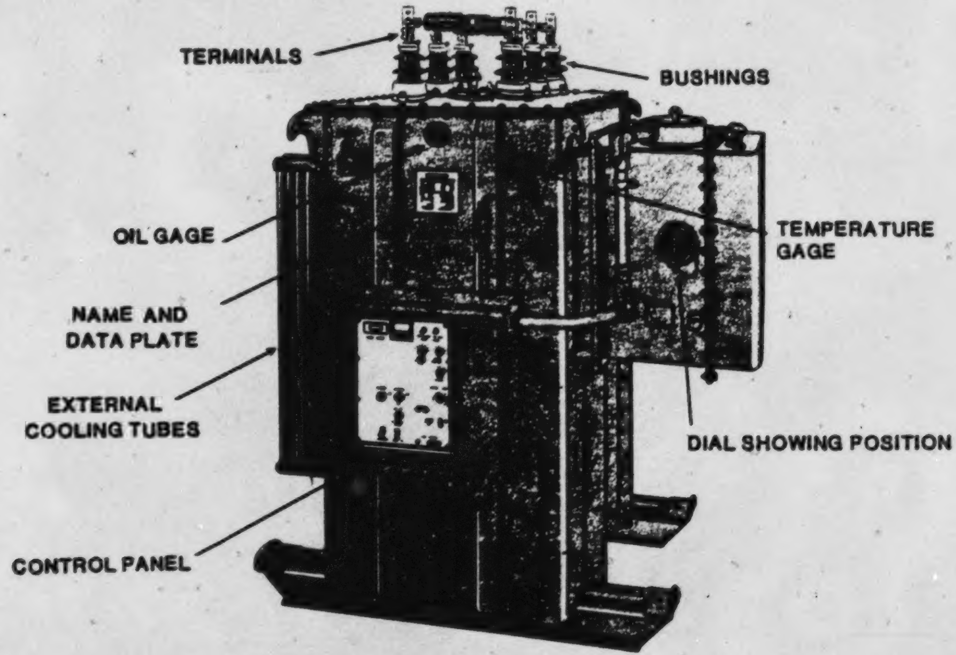

TERMINALS
BUSHINGS
OIL GAGE
TEMPERATURE GAGE
NAME AND DATA PLATE
EXTERNAL COOLING TUBES
DIAL SHOWING POSITION
CONTROL PANEL

Figure 6. Substation Voltage Regulator.

6

CIRCUIT BREAKERS

When a circuit carrying a large amount of power at high voltage is interrupted, an arc forms between the switch contacts. Circuit breakers are used to break the connection and extinguish the resulting arc without damage to the equipment or danger to the operator. Three types of high voltage circuit breakers are in common use.

Figure 7 shows the components of an oil circuit breaker commonly used for transmission and distribution service. When this circuit breaker opens, the main contacts open first and the current is carried by the arcing contacts. As they open, an arc is formed inside the arc chamber. This arc is quenched by the inrush of oil as the arcing contacts are withdrawn from the arc chambers. The circuit is interrupted in about five to eight cycles.

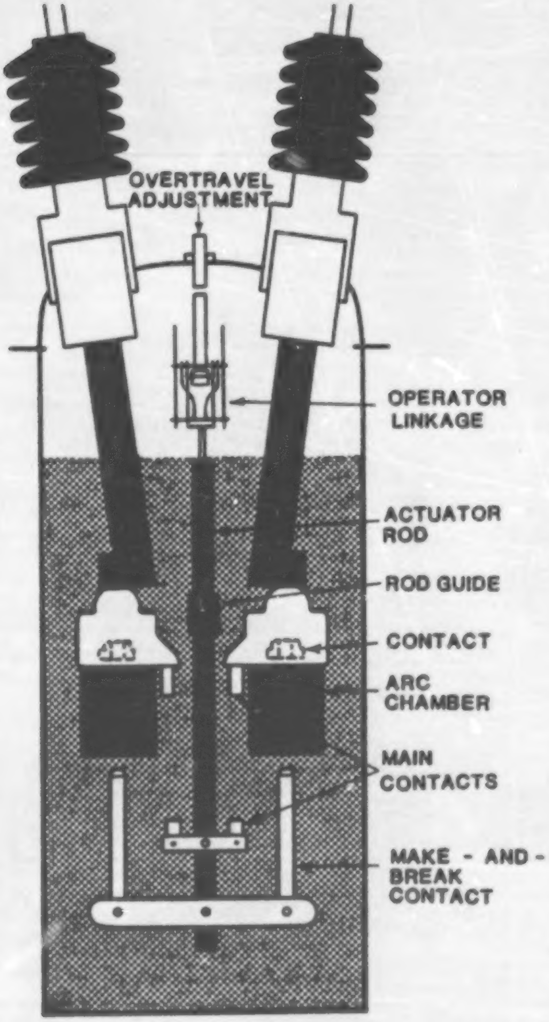

OVERTRAVEL ADJUSTMENT
OPERATOR LINKAGE
ACTUATOR ROD
ROD GUIDE
CONTACT
ARC CHAMBER
MAIN CONTACTS
MAKE - AND - BREAK CONTACT

Figure 7. Typical Oil Breaker.

Figure 8 shows a typical oil circuit breaker used in a distribution substation. This model consists of three separate breakers in separate containers. Smaller models may have all three breakers in a single tank. The tank is usually at ground potential and is insulated from high voltage by oil. Some oil circuit breakers have smaller oil tanks and the tank is not at ground potential. This was the first type of circuit breaker developed and it remains the most popular.

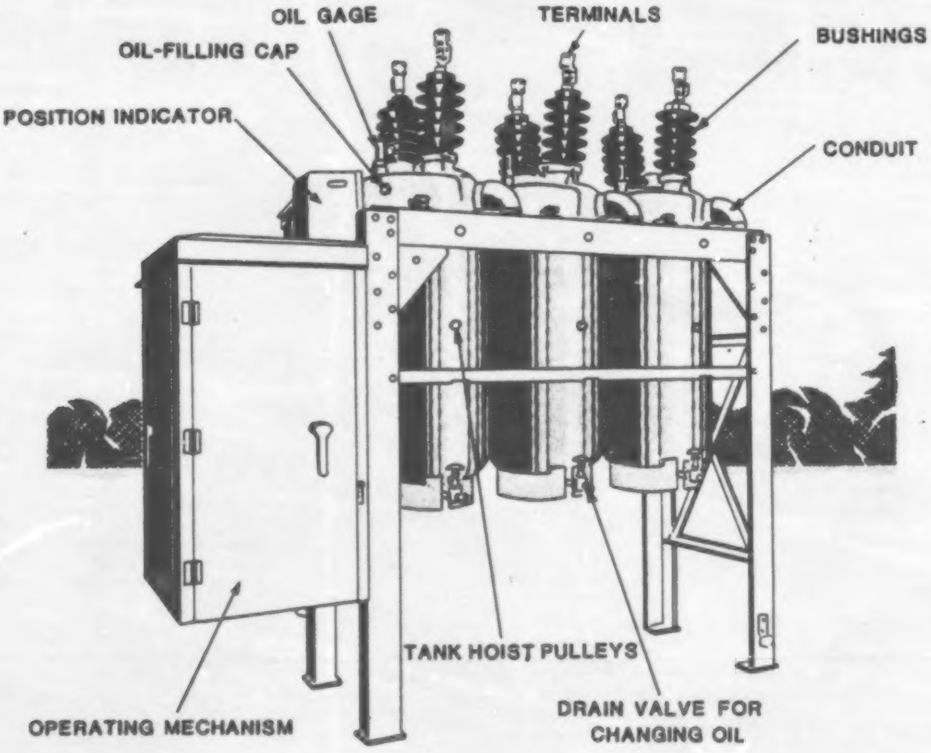
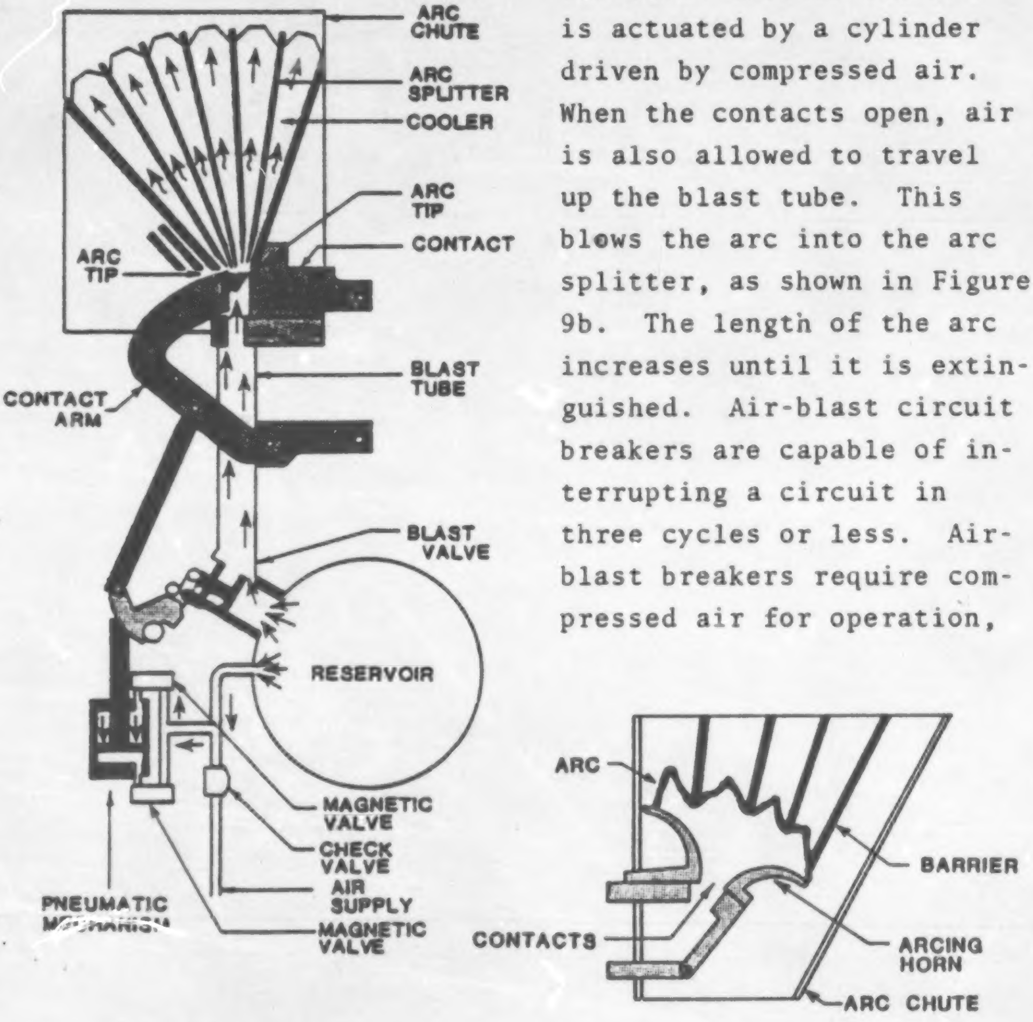

OIL GAGE
TERMINALS
BUSHINGS
OIL-FILLING CAP
POSITION INDICATOR
CONDUIT
TANK HOIST PULLEYS
DRAIN VALVE FOR CHANGING OIL
OPERATING MECHANISM

Figure 8. Substation Oil Circuit Breaker.

Figure 9a shows the components of an air-blast circuit breaker. In this device, a blast of compressed air is used to blow out the arc. The air-blast circuit breaker is actuated by a cylinder driven by compressed air. When the contacts open, air is also allowed to travel up the blast tube. This blows the arc into the arc splitter, as shown in Figure 9b. The length of the arc increases until it is extinguished. Air-blast circuit breakers are capable of interrupting a circuit in three cycles or less. Air-blast breakers require compressed air for operation,


ARC CHUTE
ARC SPLITTER
COOLER
ARC TIP
CONTACT
ARC TIP
BLAST TUBE
CONTACT ARM
BLAST VALVE
RESERVOIR
MAGNETIC VALVE
CHECK VALVE
AIR SUPPLY
PNEUMATIC MECHANISM
MAGNETIC VALVE
ARC
BARRIER
CONTACTS
ARCING HORN
ARC CHUTE

a. Blast of Air Released Simultaneously With Opening of Contacts

b. Interruption of Arc

Figure 9. Air-Blast Circuit Breakers.

but contain no oil to be contaminated or present a fire hazard. Air-blast breakers have become popular for indoor installations and are used in many outdoor substations. Figure 10 shows air-blast circuit breakers for extra high voltage (ehv) operation.

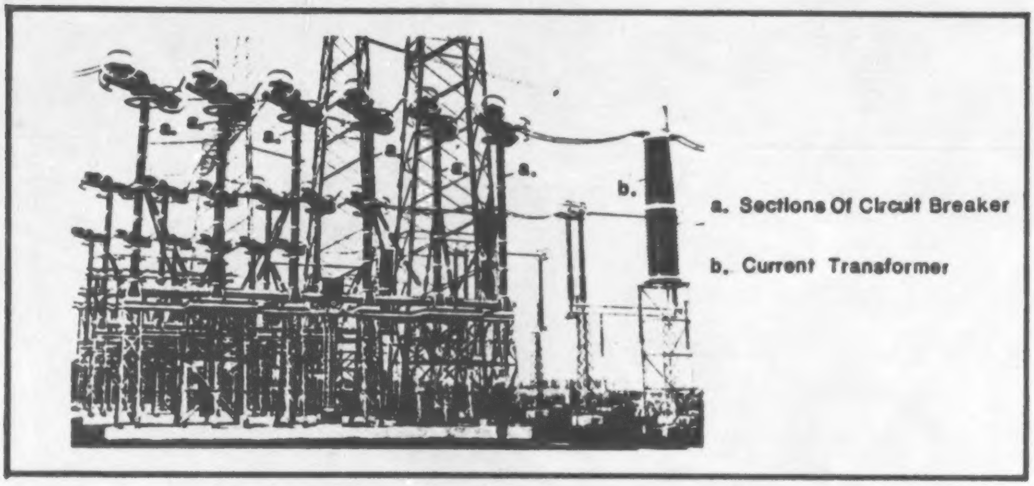


Figure 10. Air-Blast Circuit Breaker Rated at 375 kV.

Figure 11 illustrates the operation of a gas circuit breaker. This device consists of two sets of contacts mounted on a rotating arm inside a chamber filled with sulphur hexafluoride (SF_6) gas at about 60 pounds per square inch (psi). As the contacts open, a blast of gas at about 240 psi is forced through the contacts and blows out the arc. SF_6 is used because it has a very high dielectric current that increases with pressure. It conducts less than oil and extinguishes the arc more rapidly.

Figure 12 shows a gas circuit breaker used to remove a generator from the power grid. These breakers are expensive and require a compressor and filtering system for the gas. They are used primarily for high voltage, high current service.

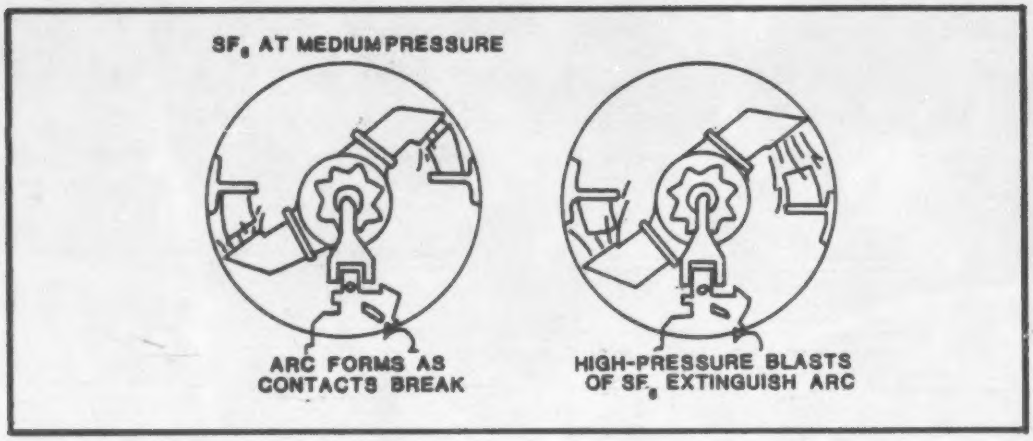

SF_6 AT MEDIUM PRESSURE
ARC FORMS AS CONTACTS BREAK
HIGH-PRESSURE BLASTS OF SF_6 EXTINGUISH ARC

Figure 11. Dual Pressure SF_6 Gas Circuit Breaker (GCB).

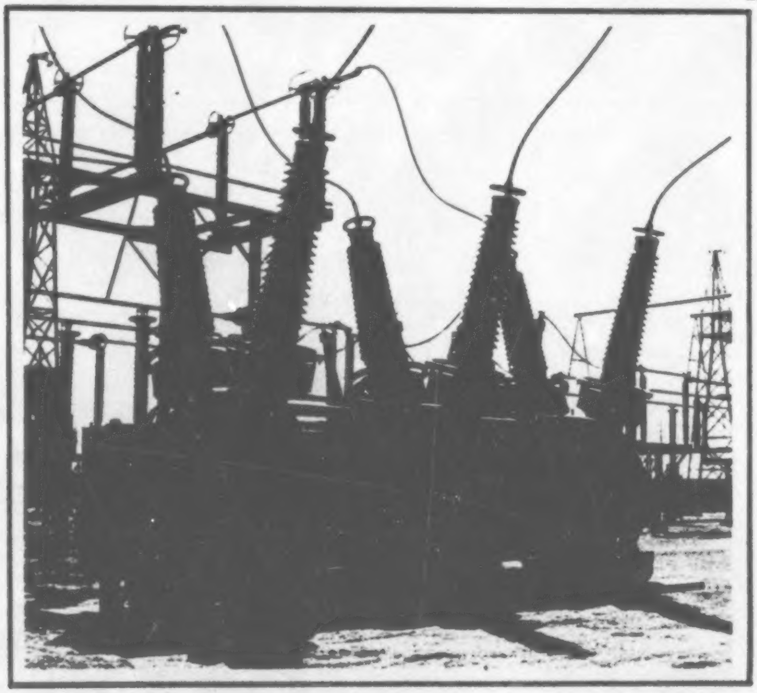


Figure 12. Gas Circuit Breaker.

DISCONNECT SWITCHES

Figure 13 shows a disconnect switch used to disconnect circuits manually. The stationary switch contacts are supported by the insulator stack on the right. The switch blade is supported by the center stack. The left stack is the driving mechanism. Rotating the driving stack causes the switch blade to rise vertically, assuring that the circuit opens. This type of switch cannot be used to break an energized circuit. It is always used with a circuit breaker and is opened after the circuit breaker is opened. Purpose of the disconnect switch is to make the circuit remain de-energized during maintenance or repair. Vertical-break disconnect switches are used widely throughout transmission and distribution systems to isolate system components.

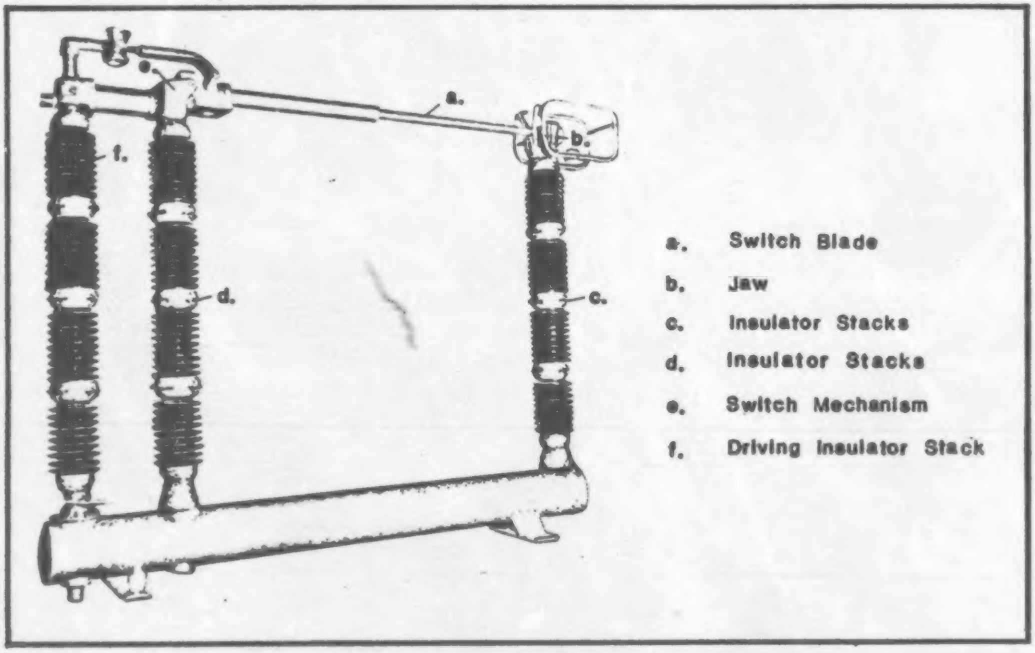

a.
b.
f.
d.
c.
a. Switch Blade
b. Jaw
c. Insulator Stacks
d. Insulator Stacks
e. Switch Mechanism
f. Driving Insulator Stack

Figure 13. Vertical-Break Disconnecting Switch.

Figure 14 is a motorized disconnect switch that can be used to interrupt a current in a circuit. It is operated in the same manner as the previous switch, but is powered by a motor and incorporates a nitrogen blast to extinguish the arc. This type of switch is used in many distribution substations for normal switching applications. The motor-operated disconnect switch is not a replacement for a circuit breaker for circuit protection, as it operates only at relatively low currents.

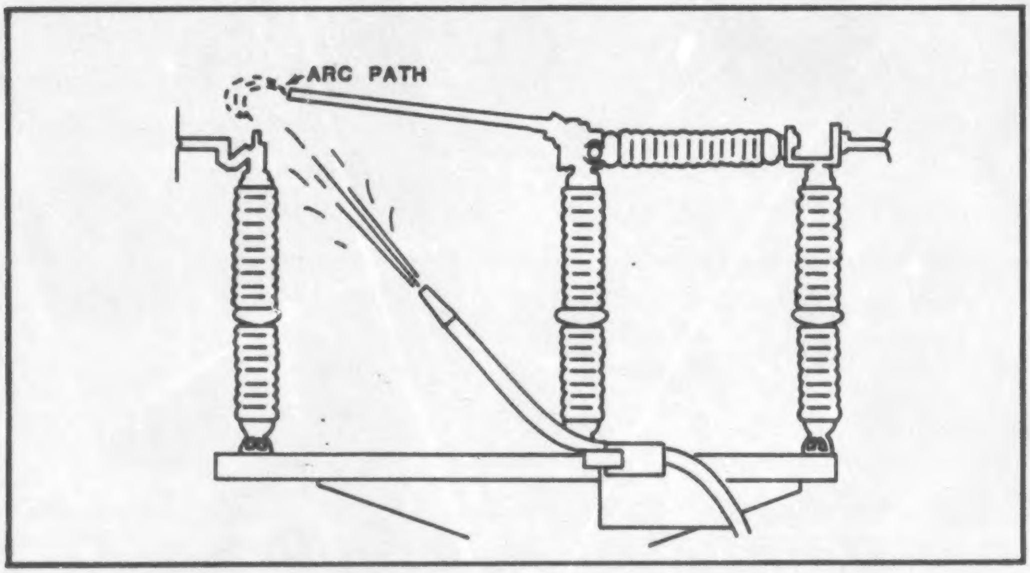


Figure 14. Nitrogen Blast Helps Extinguish Arc in Motor-Operated Disconnect (MOD).

INSTRUMENTATION

Substations include a variety of monitoring and recording devices. Quantities measured include volts, amps, power in watts, reactive power in vars (volt-amp reactive), frequency — and perhaps, power factor. Most of the meter movements used operate at 120 V and 5 amps, although their calibration is in terms of quantities measured. Signals are provided to substation meters by current and voltage transformers designed for use with specific meters. Figure 15 is a potential transformer that steps the transmission line voltage down to approximately 102 V. Its primary winding is connected across the voltage to be measured. Its secondary is connected to a meter that is calibrated to indicate the true transmission line voltage.

Figure 16 shows two types of current transformers. The primary of the current transformer is in series with the line carrying the current to be measured, and the output of the transformer is proportional to the total current. The secondary of the current transformer is connected to an ammeter that is calibrated to indicate the line current.

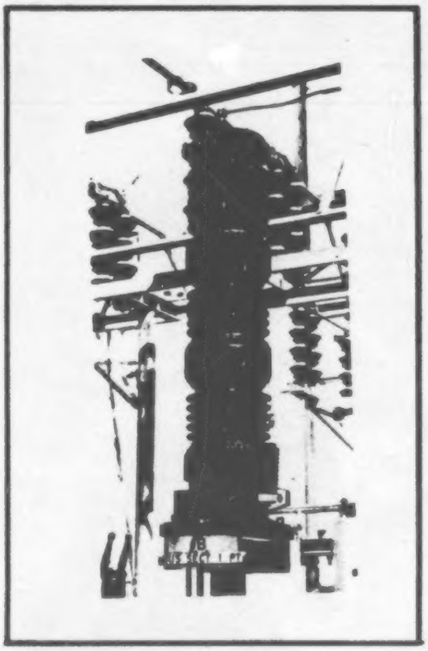


Figure 15. Potential (Voltage) Transformer.

Figure 17 shows current and voltage transformers in a measuring circuit. These transformers also provide the signals used to operate relays that open circuit breakers in case of faults, change taps on voltage regulators, and switch in reactors for power factor correction.

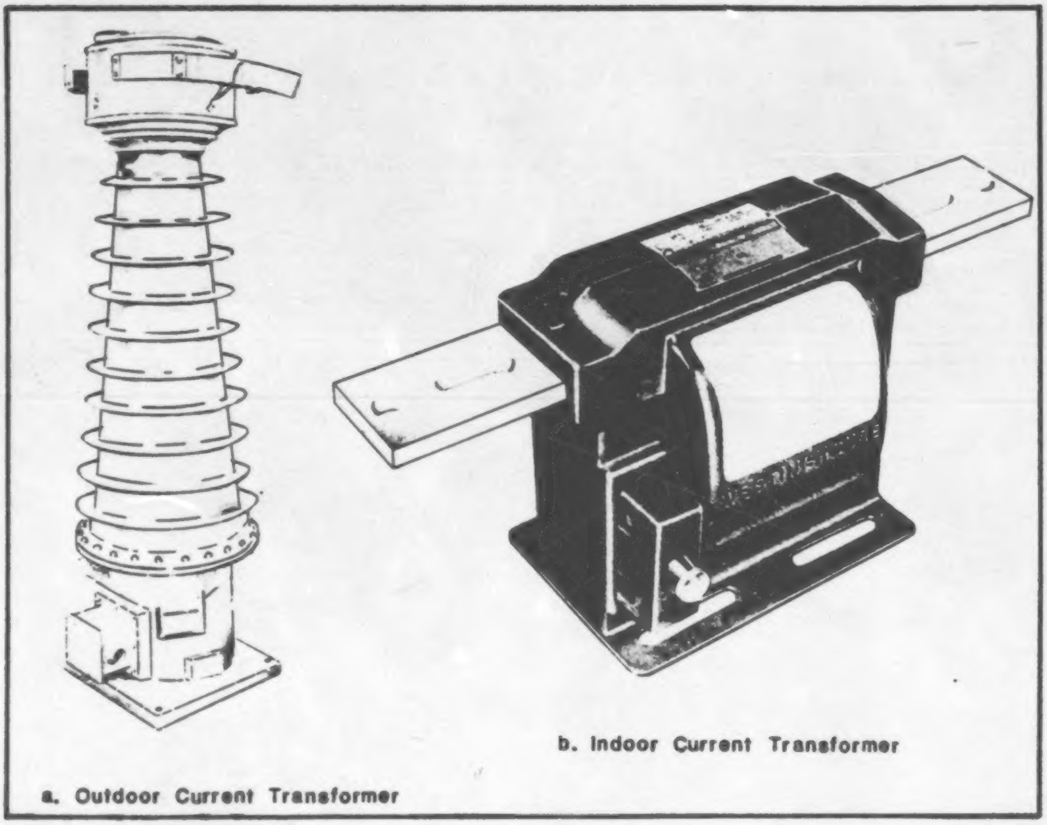

b. Indoor Current Transformer
a. Outdoor Current Transformer

Figure 16. Current Transformers.

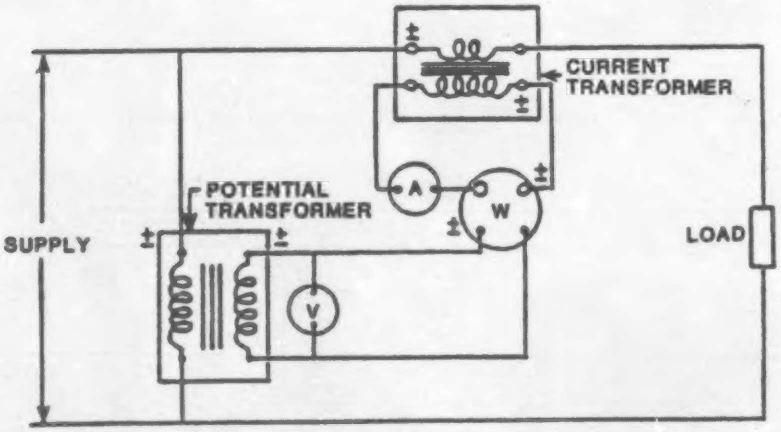

CURRENT TRANSFORMER
POTENTIAL TRANSFORMER
SUPPLY
LOAD
A
W
V
±

Figure 17. Connection of Instrument Transformers.

POWER FACTOR CORRECTION

Most leads and most transmission systems have more inductance than reactance, resulting in a lagging power factor. This is often corrected by capacitors. Capacitors are located in substations, mounted on poles, or placed in underground vaults along the transmission lines. Capacitors are switched into the circuit automatically when needed. When large amounts of power are involved, a device called a synchronous condenser is used. A synchronous condenser is a rotating machine that is similar to a synchronous motor with no load. The synchronous condenser has a continuously adjustable power factor that can provide either leading or lagging reactive power.

In underground cables and ehv transmission lines, the capacitance of the lines may be so great that a leading power factor is produced. This is corrected by installing a shunt reactor. This is an inductor that offsets the capacitance of the line.

PROTECTIVE RELAYING

Relays are used in conjunction with current and voltage transformers to control circuit breakers to prevent overcurrent and over-voltage conditions. The design, characteristics, and applications of protective relays for transmission and distribution systems are the same as those for industrial applications. These are described in Module PI-03, "Industrial Electrical Distribution."

A TYPICAL SUBSTATION

Figure 18 is a schematic diagram of a typical distribution substation. Figure 19 identifies the symbols used in such schematics.

SUMMARY

Electrical power transmission and distribution systems do not exist in isolation, but are tied together in a power grid that connects each utility to its neighbors. The transmission system consists of overhead and underground cables to carry the power and switching stations and substations that contain the monitoring and control equipment. These stations must direct power to customers and assure that power is delivered at the proper voltage and power factor. They must also provide protection for the system.

Substations typically include the following components:

- Power transformers for changing the voltage level.
- Voltage regulators for adjusting the delivered voltage as changing current causes changes in the voltage drop in the transmission lines.
- Circuit breakers for connecting and disconnecting circuits.
- Disconnect switches for disconnecting lines or components after the circuit breaker is opened.
- Voltage and current transformers for monitoring and controlling the system.
- A variety of measuring and recording equipment.

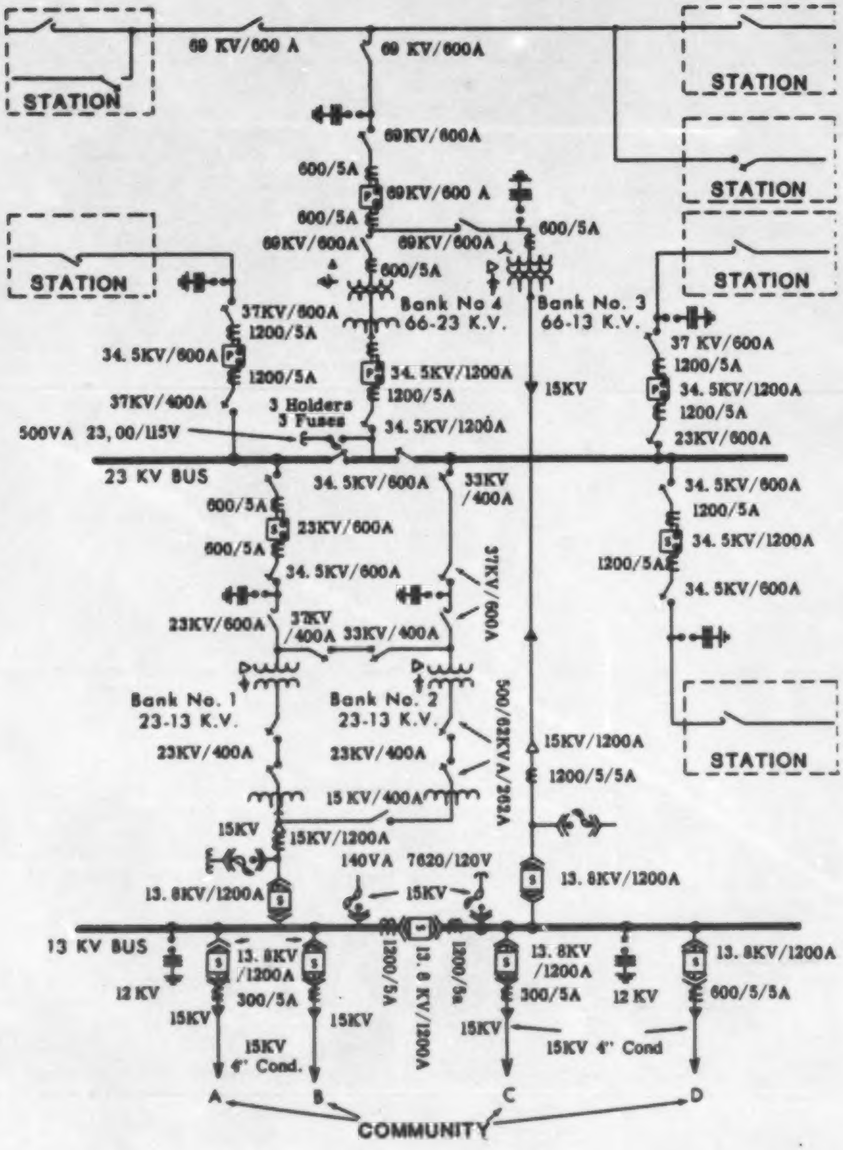

STATION
69 KV/600 A
69 KV/600A
STATION
69KV/600A
600/5A
69KV/600 A
STATION
600/5A
600/5A
69KV/600A
69KV/600A
STATION
600/5A
STATION
Bank No 4
66-23 K.V.
Bank No. 3
66-13 K.V.
37KV/600A
1200/5A
37 KV/600A
34. 5KV/600A
1200/5A
1200/5A
34. 5KV/1200A
15KV
34. 5KV/1200A
1200/5A
1200/5A
37KV/400A
3 Holders
3 Fuses
500VA 23, 00/115V
34. 5KV/1200A
23KV/600A
23 KV BUS
34. 5KV/600A
33KV
/400A
34. 5KV/600A
600/5A
1200/5A
23KV/600A
34. 5KV/1200A
600/5A
1200/5A
34. 5KV/600A
37KV/600A
34. 5KV/600A
23KV/600A
37KV
/400A
33KV/400A
Bank No. 1
23-13 K.V.
Bank No. 2
23-13 K.V.
500/62KVA/262A
STATION
23KV/400A
23KV/400A
15KV/1200A
1200/5/5A
15 KV/400A
15KV
15KV/1200A
140VA
7620/120V
15KV
13. 8KV/1200A
13. 8KV/1200A
13 KV BUS
13. 8KV
/1200A
1200/5A
13. 8 KV/1200A
1200/5a
13. 8KV
/1200A
13. 8KV/1200A
12 KV
300/5A
300/5A
12 KV
600/5/5A
15KV
15KV
15KV
15KV
4" Cond.
15KV 4" Cond
A
B
C
D
COMMUNITY

Figure 18. Typical Substation Layout.

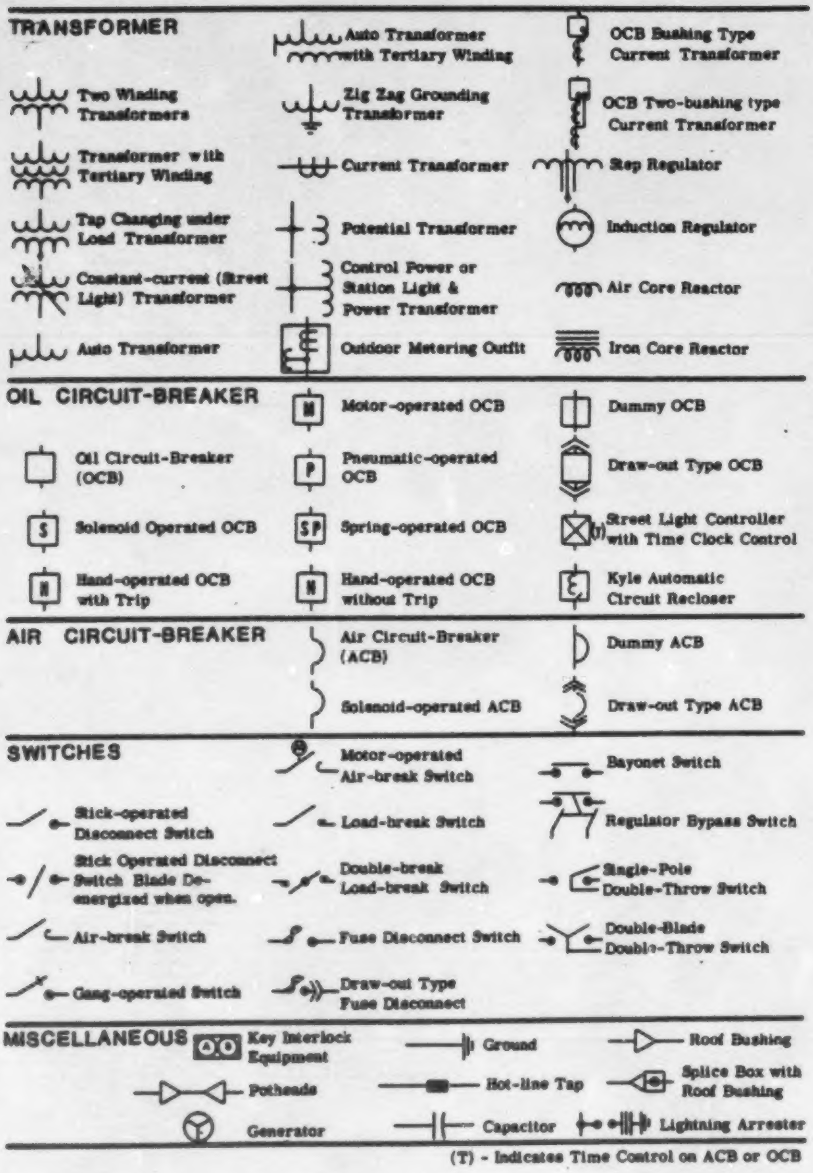

TRANSFORMER
Two Winding Transformers
Transformer with Tertiary Winding
Tap Changing under Load Transformer
Constant-current (Street Light) Transformer
Auto Transformer
Auto Transformer with Tertiary Winding
Zig Zag Grounding Transformer
Current Transformer
Potential Transformer
Control Power or Station Light & Power Transformer
Outdoor Metering Outfit
OCB Bushing Type Current Transformer
OCB Two-bushing type Current Transformer
Step Regulator
Induction Regulator
Air Core Reactor
Iron Core Reactor
OIL CIRCUIT-BREAKER
Oil Circuit-Breaker (OCB)
Solenoid Operated OCB
Hand-operated OCB with Trip
Motor-operated OCB
Pneumatic-operated OCB
Spring-operated OCB
Hand-operated OCB without Trip
Dummy OCB
Draw-out Type OCB
Street Light Controller with Time Clock Control
Kyle Automatic Circuit Recloser
AIR CIRCUIT-BREAKER
Air Circuit-Breaker (ACB)
Solenoid-operated ACB
Dummy ACB
Draw-out Type ACB
SWITCHES
Stick-operated Disconnect Switch
Stick Operated Disconnect Switch Blade De-energized when open.
Air-break Switch
Gang-operated Switch
Motor-operated Air-break Switch
Load-break Switch
Double-break Load-break Switch
Fuse Disconnect Switch
Draw-out Type Fuse Disconnect
Bayonet Switch
Regulator Bypass Switch
Single-Pole Double-Throw Switch
Double-Blade Double-Throw Switch
MISCELLANEOUS
Key Interlock Equipment
Potheads
Generator
Ground
Hot-line Tap
Capacitor
Roof Bushing
Splice Box with Roof Bushing
Lightning Arrester
(T) - Indicates Time Control on ACB or OCB

Figure 19. Symbols for Substation Equipment.

EXERCISES

1. Use the symbols shown in Figure 19 to identify each component in Figure 18. Redraw the substation schematic showing only circuit breakers, power transformers, voltage regulators, and disconnect switches.
2. Explain the operation of the following types of circuit breakers:
   a. Oil
   b. Air-blast
   c. Gas
3. Diagram the operation of a lightning arrester. Explain the diagram.
4. Explain the applications of the following types of transformers:
   a. Power transformer
   b. Voltage regulator transformer
   c. Current transformer
   d. Voltage transformer
5. Explain the difference in the operation of the tap changers of a power transformer and a voltage regulator.
6. Explain the function of disconnect switches and how this differs from the function of circuit breakers.
7. Explain how to correct the power factor at a substation if it is:
   a. Leading
   b. Lagging

LABORATORY MATERIALS

Spiral notebook or clipboard.
Pen or pencil.
Camera (optional).

LABORATORY PROCEDURES

This laboratory exercise consists of a field trip to at least one — and preferably two — substations. The purpose is to acquaint the student with the equipment, controls, and operation of such facilities. If possible, the stations visited should be different in function as to the transmission and distribution system. One should be a distribution substation supplying residential or small commercial customers. The other substation should be a switching station or a power plant transmission station.

1. Observe the station components during the familiarization tour. Observe all safety precautions. As much of the laboratory as possible should be completed from outside the station compound.
2. Sketch the transmission lines entering and leaving the station. Record the voltage and rated current of the lines and the type of customer served by the distribution system.
3. Sketch the layout of the station and identify the following components:
   a. Power transformers
   b. Circuit breakers
   c. Voltage regulators
   d. Disconnect switches
   e. Capacitor banks, if present

4. List the ratings and specifications of the above equipment in the Data Table (in sprial notebook or on clipboard paper).
5. Sketch the bus system used to connect the station components.
6. List the quantities monitored by the station monitoring equipment.
7. Sketch any additional components that are present, such as lightning arresters, current and voltage transformers, fuses, and controls.
8. List maintenance procedures for the station if this information is available.
9. Repeat the procedure for the second station.
10. Prepare a report describing the station and its operation.

NOTE: Several options may be used in fulfilling this laboratory procedure. One possibility is to take a camera and photograph the station and its components. Another option is to tour one station and then divide into several groups and visit several substations in the area. Much information may be obtained from observation of substations from outside the fences surrounding them. In this manner, a number of substations may be compared.

DATA TABLES

List all available data and make all field sketches in a spiral notebook - or include this information in a folder to be turned in with the final laboratory report.

REFERENCES

Burns, David and Fink, Lowell H. Transmission Lines. Scranton, PA: Intext, Inc., 1976.

Commonwealth Edison Co. Power Plant Electrical Fundamentals Book 5. Commonwealth Edison Co., 1979.

Pansini, Anthony J. Basic Electrical Power Distribution, Vol. 1 and 2. Rochelle Park, NJ: Hayden Book Company, Inc., 1971.

Power Magazine. "In Plant Electrical Distribution — A Special Report," Power (James J. O'Connor, Editor). New York: 1965.

Rowan, W.O. Electrical Power Substations, Part 1 and Part 2. Scranton, PA: Intext, Inc., 1973.

Technical Education Research Center — Southwest. Module EM-03, "Transformers," Electromechanical Devices. Waco, TX: Technical Education Research Center — Southwest, 1979.

Please circle the appropriate answer.

1. Power transformers ...
   - a. have multiple output taps that can usually be changed under load.
   - b. have efficiencies of about 95%.
   - c. must be disconnected from power before their output taps can be changed.
   - d. have no provisions for changing the output voltage.
   - e. Only b and c are true.
2. Extra high voltage transmission lines ...
   - a. usually have more capacitance than inductance.
   - b. operate at voltages in the 735 kV range.
   - c. are used for long distance transmission only.
   - d. All the above are true.
   - e. Only b and c are true.
3. The cables used for overhead transmission lines are usually made of ...
   - a. copper.
   - b. aluminum.
   - c. steel.
   - d. a combination of copper and aluminum.
   - e. a combination of aluminum and steel.
4. Distribution substations probably will not include ...
   - a. oil circuit breakers.
   - b. air-blast circuit breakers.
   - c. gas circuit breakers.
   - d. voltage regulators.
   - e. disconnect switches.

5. A leading power factor of a long transmission line may be corrected by connecting ...
    a. a shunt inductor.
    b. a shunt capacitor.
    c. a synchronous condenser.
    d. Either a or c is true.
    e. Either b or c is true.

6. Current transformers ...
    a. are connected across two phases of a three-phase circuit.
    b. are used to increase the current in a distribution line.
    c. are used to monitor the current in a single conducting wire.
    d. are not used in protective relaying as are voltage transformers.
    e. None of the above are correct.

7. A 35 kV line is classed as a ...
    a. distribution line.
    b. transmission line.
    c. subtransmission line.
    d. extra high voltage line.
    e. generator supply line.

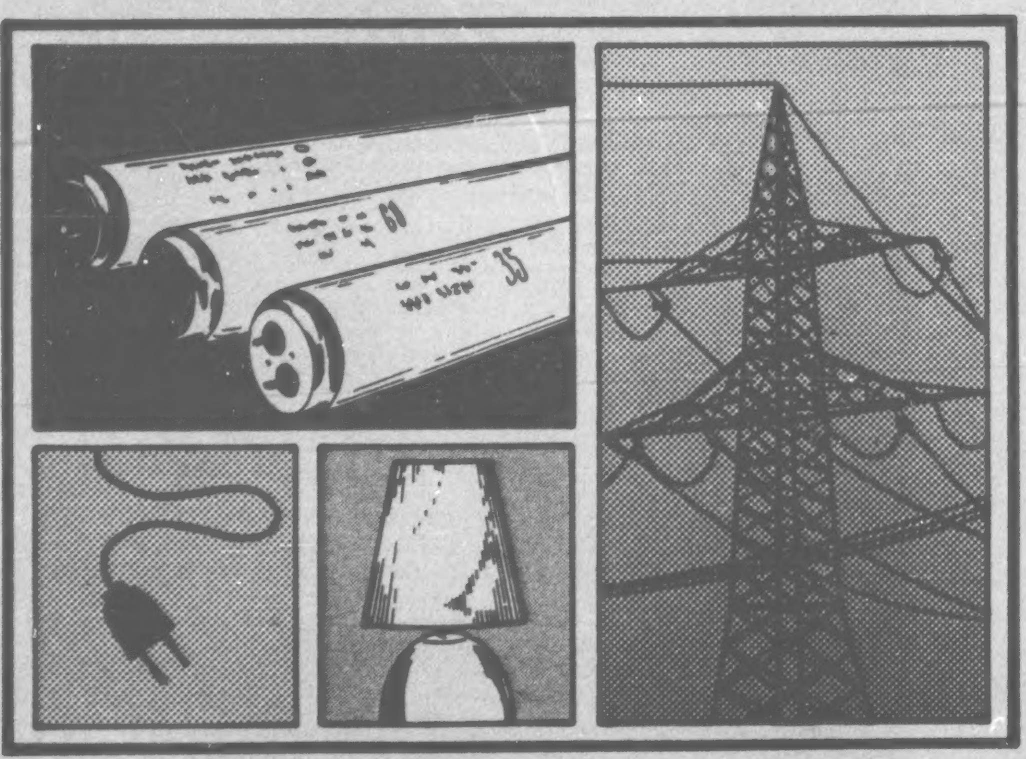
8. Motorized disconnect switches ...
    a. are an inexpensive replacement for oil circuit breakers for circuit protection.
    b. can never be used to open a circuit in which current is flowing.
    c. often incorporates SF_6 gas to quench the arc formed when they open.
    d. cannot be used at normal distribution voltages.
    e. None of the above are correct.

9. Oil circuit breakers ...
   a. usually have an oil tank that is at ground potential.
   b. are the most common type in distribution systems.
   c. may be controlled by relays operated from current transformers.
   d. All of the above are correct.
   e. None of the above are correct.

10. Air-blast circuit breakers ...
   a. do not operate as quickly as oil circuit breakers.
   b. may be used either for indoor or outdoor installations.
   c. can be used only at subtransmission and distribution voltages.
   d. Only a and b are true.
   e. None of the above are true.

ENERGY TECHNOLOGY
CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-03
INDUSTRIAL ELECTRICAL DISTRIBUTION

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

The purpose of an industrial plant is to produce a product as economically and efficiently as possible. Since electrical energy plays an important role in the production and packaging of virtually every product produced, the electrical power delivery system is always important in every plant.

The size, voltage, and complexity of the systems employed vary widely with the type and size of installation served. However, all systems must deliver adequate power to the point of application –

- at the proper voltage
- with minimum power losses
- and an acceptable reliability,
- while providing adequate protection of equipment
- and insuring the safety of personnel.

This module discusses the design of systems to provide such service in industrial settings and the components used in such systems. Topics presented include basic design of primary and secondary substations, the selection of distribution voltages, grounding schemes, circuit protection schemes, and the equipment employed for circuit protection.

The laboratory section of this module is a field trip to an industrial plant where the students will examine the electrical distribution system.

PREREQUISITES

The student should have completed Module PI-02, "Electrical Power Transmission and Distribution."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and label a diagram showing basic components of the primary substation of a typical radial distribution system. Explain the purpose of each component.
2. Draw simplified diagrams of three other equipment arrangements that may be used in primary substations to increase reliability.
3. Draw and label diagrams showing the following types of secondary distribution substations:
    a. Radial
    b. Primary selective
    c. Secondary selective
    d. Networks
4. Specify the distribution voltages indicated by the terms "high voltage," "medium voltage," and "low voltage." List the common distribution voltages in the low voltage range.
5. Explain the term "480Y/277 V" and the reasons for the popularity of this distribution voltage.
6. Draw a diagram showing the connections of the transformer secondaries for a 480Y/277 V system. Indicate the phase-to-phase voltage and the phase-to-ground voltage. Show the connections for solid grounding of the system.
7. Explain the following grounding schemes and the application of each:
    a. Equipment grounding
    b. System grounding
    c. Solid grounding

    d. Low resistance grounding
    e. High resistance grounding

8. List and explain the five factors that must be considered when selecting circuit protection devices.
9. Describe the characteristics and application of the following types of fuses:
    a. One-time
    b. Lag
    c. Dual element
    d. Current-limiting

10. Describe the construction, operation, and voltage ranges of air-magnetic circuit breakers and molded-case air circuit breakers.
11. Describe the characteristics and operation of the following types of relays:
    a. Plunger
    b. Time-delay induction disk
    c. Balanced beam differential

12. Explain selective tripping and cascade tripping of overcurrent protection devices.
13. Visit an industrial electrical power distribution system. Examine the system and its components and prepare a report describing the system.

PRIMARY SUBSTATIONS

The primary substation is the point of entry of the electrical power into the plant. The substation may be owned by either the utility or the customer, but the trend is toward customer-owned primary substations, especially for larger plants.

Voltage supplied to the primary substation depends upon the power requirements of the installation. Smaller plants are supplied with the standard 13,800 V distribution voltage. Larger facilities can be supplied directly from subtransmission lines at 35 kV, or transmission lines at 69 kV or 138 kV. The primary substation contains protective devices and power transformers to reduce the voltage to the plant distribution voltage. Distribution voltages are usually classified as low voltage (600 V or less), medium voltage (601 V to 15,000 V) and high voltage (above 15,000 V).

Voltage regulation is usually accomplished in the primary substation if it is required. For most smaller installations, this is accomplished at previous stations in the transmission system.

The primary substations of plants with higher voltage service are outdoor facilities similar to switching substations in the transmission system. Plants with 13.8 kV primaries may have outdoor primary substations, but most of these are outside, also. This is because of the difficulties in bringing higher voltages than necessary into buildings.

Most smaller primary substations are preassembled with metal-enclosed switchgear. This allows standard designs and components and reduces installation cost.

PRIMARY SUBSTATION DESIGN

The design of the primary substation depends upon the plant load and the reliability of electrical service necessary. Figure 1 shows the basic components and layout of a typical primary substation used in most plants. This scheme is called radial distribution, because all power is supplied radially from a single distribution point and one primary line.

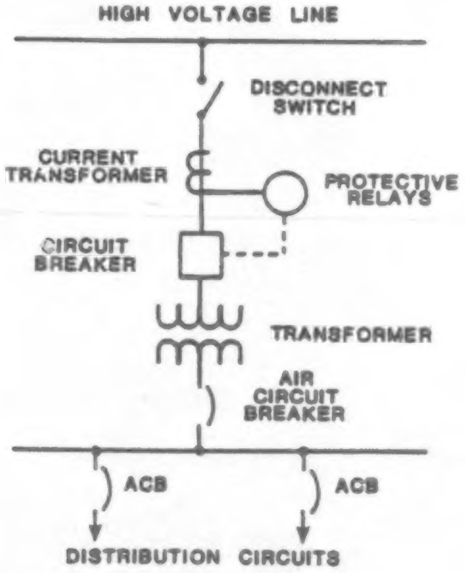

HIGH VOLTAGE LINE
DISCONNECT SWITCH
CURRENT TRANSFORMER
PROTECTIVE RELAYS
CIRCUIT BREAKER
TRANSFORMER
AIR CIRCUIT BREAKER
ACB
ACB
DISTRIBUTION CIRCUITS

Figure 1. Primary Substation of Typical Radial Distribution Scheme.

The high voltage side of the substation includes a circuit breaker capable of interrupting the short circuit current of the installation. This is usually an oil circuit breaker, but air-blast circuit breakers may be used, especially in indoor installations. A disconnect switch is also provided to remove power from the substation after the circuit breaker is opened. The secondary side of the transformer is connected to another circuit breaker. At voltages of 13.8 kV and below, this is usually an air circuit breaker. This type of circuit breaker is described later in this module. From this breaker, the power is connected to the main feeder lines. These may be insulated cables in conduits or racks, or busses enclosed in busways. Each takeoff from the main line is usually equipped with its own circuit breaker.

The radial distribution substation is the simplest and least expensive, but has the lowest reliability. Failure of any component in the primary station results in a power loss in the entire plant. This is adequate for most applications, but some industries experience major losses as a result of even a momentary power failure.

INCREASING RELIABLITY OF PRIMARY SUBSTATIONS

Many schemes may be used to increase the reliability of the primary substation. Three possibilities are shown in Figure 2.

Figure 2a is a primary loop station. It is essentially two radial distribution substations in parallel, with each carrying half of the load. If a failure occurs in one half of the station, a breaker in the main feeder bus that is normally open may be closed to supply the entire load from the other half until the fault can be repaired. If a single transformer is not rated high enough to carry the entire load, its capacity may be increased temporarily by a water spray. The current-handling capacity of almost any self-cooled transformer may be increased by 67% by this method.

Figure 2b shows another method used to increase reliability when two supply lines are available. One of the lines normally carries all of the load. If a failure occurs on this line, the station is switched to the second line with only momentary interruption of service.

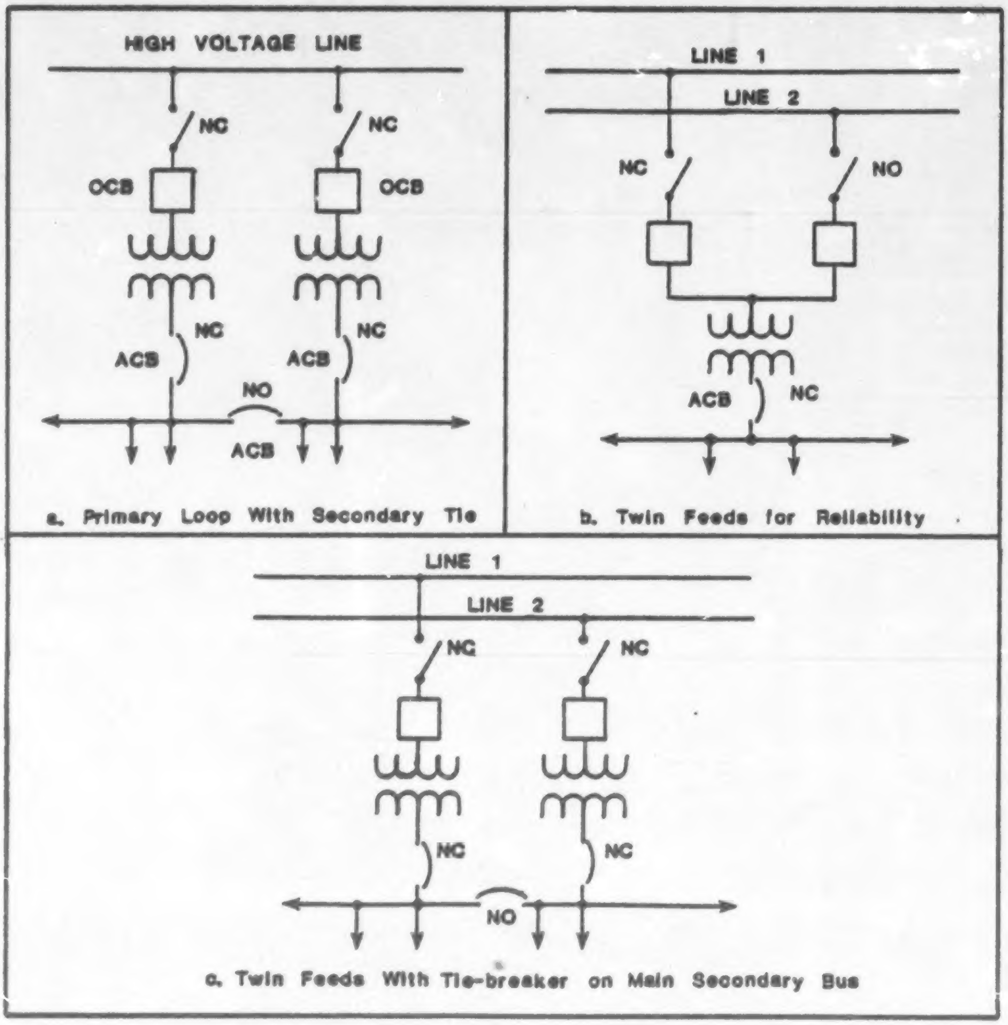

HIGH VOLTAGE LINE
NC
NC
OCB
OCB
NC
NC
ACB
ACB
NO
ACB
a. Primary Loop With Secondary Tie
LINE 1
LINE 2
NC
NO
ACB
NC
b. Twin Feeds for Reliability
LINE 1
LINE 2
NC
NC
NC
NC
NO
c. Twin Feeds With Tie-breaker on Main Secondary Bus

Figure 2. Schemes for Increasing
Primary System Reliability.

Figure 2c is a combination of the two previous techniques. This arrangement is the most expensive to install, but twin feeds with a tie-breaker on the main secondary bus afford maximum reliability.

SECONDARY SUBSTATIONS

Plants with relatively small power requirements and distribution line lengths of less than 200 feet may have only a primary substation that supplies the distribution system with the voltage that is utilized by the equipment. In larger plants, or plants with longer distribution lines, the distribution system often carries a higher voltage than is used by the equipment. This allows the same amount of power to be delivered to the point of application at a lower current, reducing both the power loss and the voltage drop under load. The distribution busses or cables lead to secondary substations, often called load centers, because these secondary substations are located close to the load they serve.

SECONDARY SUBSTATION DESIGN

Secondary substations are scaled-down versions of the primary station, are usually located in the area served, and are completely enclosed in metal cabinets. As a minimum, secondary substations contain a stepdown transformer with an air circuit breaker on the output, internal busses to branch circuits, and smaller circuit breakers for the branch circuits.

Depending on the size of the load, the transformer may be either oil-filled or dry. Switchgear is typically mounted in racks and can be easily disconnected and removed for servicing. Smaller load centers consist of an enclosed dry transformer mounted on the floor (or above the work area) and a wall-mounted circuit breaker box.

SECONDARY SUBSTATION CONNECTIONS

As with primary substations, secondary substations can be connected to their loads in a variety of ways. Figure 3 shows four common distribution schemes.

The radial scheme shown in Figure 3a is by far the most common. Each load center takes its power from a single feeder and serves several branch circuits. For most applications, this system is sufficient, the least expensive, and the most simple.

Figure 3b shows the arrangement of a secondary selective substation with increased reliability. This load center contains two transformers and is served by two separate feeder lines. Under normal conditions, each half of the station serves half the load. If a fault occurs in one of the feeder lines, a tie-circuit breaker in the distribution bus may be closed to supply power to the entire load from one half of the station.

Figure 3c shows two primary selective load centers. Each may be supplied by either of two feeder lines. Thus, if a fault occurs in one feeder, the other may be used by both stations. In some cases, additional reliability may be provided by including two primary selective load stations in a single installation with a distribution bus-tie circuit breaker similar to the secondary selective system in Figure 3b.

The greatest reliability is provided by a network distribution system of the type shown in Figure 3d. The system shown has only one feeder line, but two or more feeder lines may be used. The distribution busses of this system may be connected to provide power to any part of the load from any

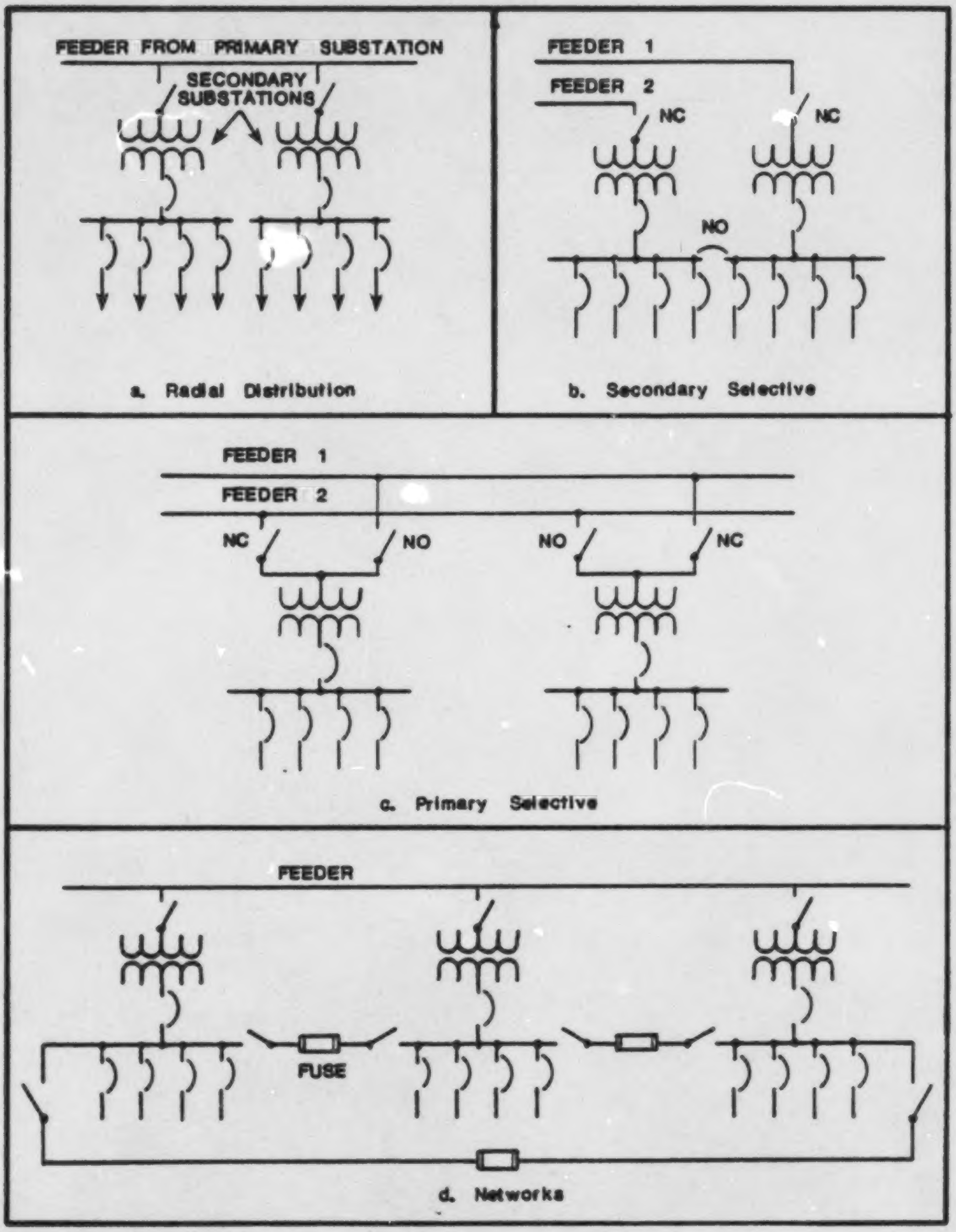

FEEDER FROM PRIMARY SUBSTATION
SECONDARY SUBSTATIONS
a. Radial Distribution
FEEDER 1
FEEDER 2
NC
NC
NO
b. Secondary Selective
FEEDER 1
FEEDER 2
NC
NO
NO
NC
c. Primary Selective
FEEDER
FUSE
d. Networks

Figure 3. Secondary Substation Connections.

one of the distribution transformers. Fuses or circuit breakers between the sections of the distribution bus provide greater circuit protection.

DISTRIBUTION VOLTAGES

Primary distribution voltages are usually either 13,800 V or 4,160 V, although higher voltages may be used in larger facilities. The output phase-to-phase voltage at the load centers may be 600, 480, 240, or 208 V. Older plants usually have 600-V systems.

Few new 600-V systems are installed today. The 408Y/277-V systems are by far the most common. They use a Y-connected secondary, illustrated in Figure 5 of this module. Such a system has a phase-to-phase voltage of 480 V, and a phase-to-ground voltage of 277 V for each phase.

The 480-V, three-phase is the most popular voltage for motors, and the 277-V, single-phase is used for fluorescent lighting. There is seldom any reason to use lower distribution voltages, and lower voltages require larger currents for the same power delivery. This means higher current ratings for breakers and larger conductors. Lower distribution voltages usually result in greater losses and higher voltage drops along the distribution lines.

The lower voltage of 240-V systems affords greater safety in damp environments like dairies and slaughter houses. Electric furnaces often operate on 240 V and are sometimes supplied by 240-V distribution lines. A more common practice is to run higher voltage busses to a load center at the furnace where the voltage is reduced.

Many smaller plants find 208Y/120 V systems practical. Three-phase motors are operated on 208 V, and the 120-V, single-phase service is used for lighting and smaller motors.

Figure 4 shows the distribution system of a plant with three larger motors and a large number of smaller ones. Service voltage of 13.8 kV is stepped down to 4,160 V for in-plant distribution. This voltage is used to operate larger

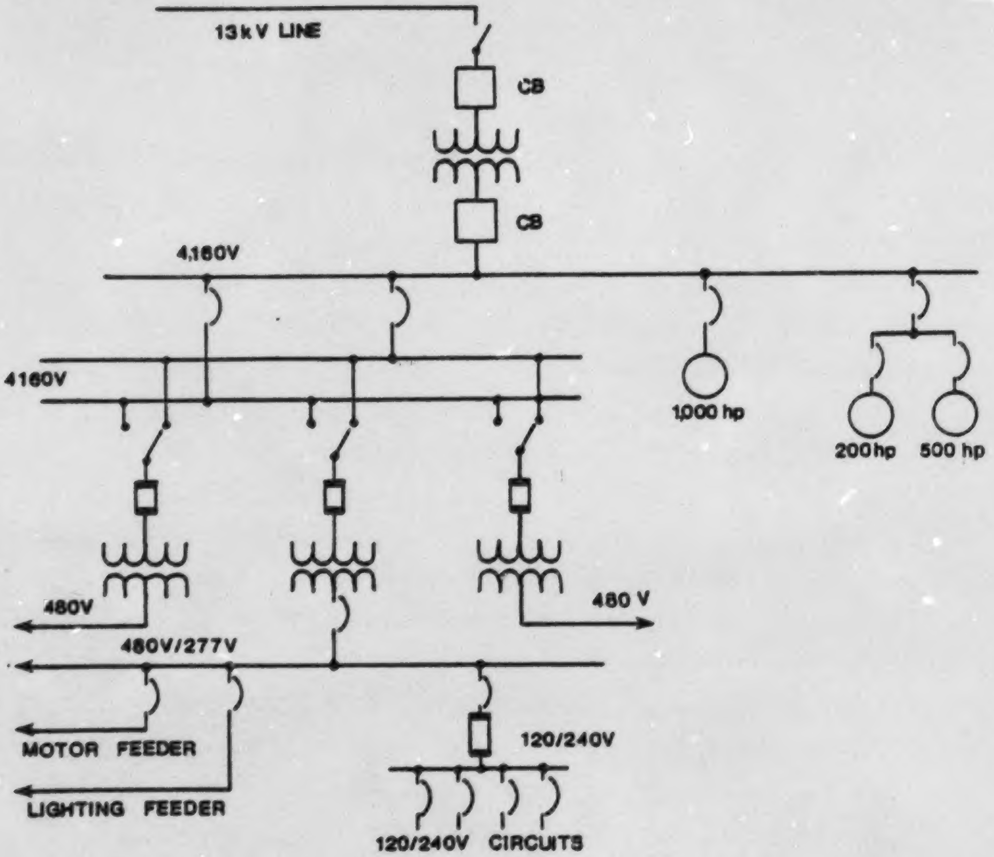

13kV LINE
CB
CB
4,160V
4160V
1,000 hp
200hp
500 hp
480V
480 V
480V/277V
MOTOR FEEDER
LIGHTING FEEDER
120/240V
120/240V CIRCUITS

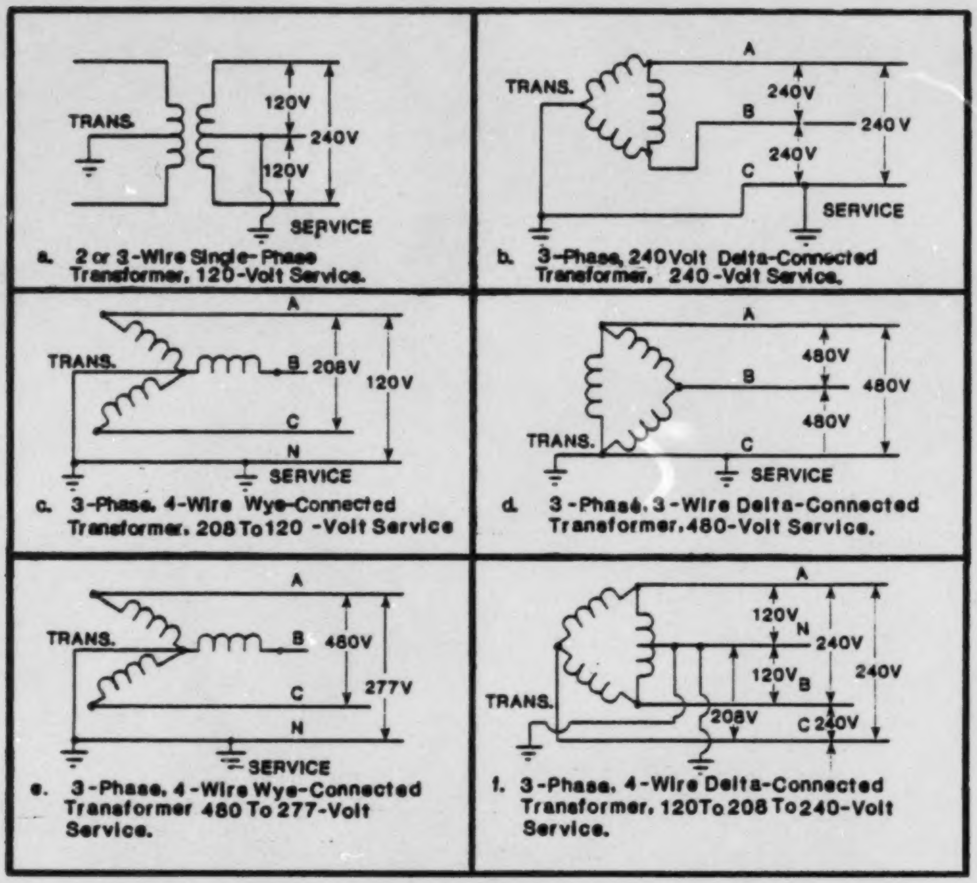
Figure 4. Industrial Power Distribution System.

motors and is distributed to load centers throughout the plant. At the load centers, voltage is reduced to 480 V for the remainder of the equipment. The 277-V, single-phase service operates the lighting; additional load centers provide 120 and 240-V, single-phase service as needed. This type system is typical for many industrial applications.

SYSTEM GROUNDING

System grounding is the intentional grounding of the electrical system at some point to increase circuit protection. This must not be confused with equipment grounding. Equipment grounding is a safety feature, consisting of grounding all non-current-carrying metal parts of the system such as motor frames, conduits, and control boxes. Equipment grounding is required for the safety of personnel. Equipment grounding connections should be of a low resistance, both to insure safety and because high-resistance junctions in equipment ground paths might result in arcs that ignite fires.

System grounding is sometimes a controversial subject and not all systems are grounded. However, most low voltage systems have some form of system ground. Figure 5 illustrates the transformer secondary connections of six systems with system grounding. This figure also illustrates the secondary connections for obtaining all common secondary distribution voltages. Figure 5c is the 480Y/277 V system used in most plants. (In a grounded Y system, the phase-to-ground voltage is the phase-to-phase voltage divided by the square root of 3.) This system provides 480-V, three-phase for motor operation and 277-V, single-phase for lighting.


TRANS.
120V
240V
120V
SERVICE
A
B
C
N
240V
240V
240V
SERVICE
208V
120V
480V
480V
480V
277V
120V
120V
208V
240V
240V
240V

a. 2 or 3-Wire Single-Phase Transformer, 120-Volt Service.

b. 3-Phase, 240 Volt Delta-Connected Transformer, 240-Volt Service.

c. 3-Phase, 4-Wire Wye-Connected Transformer, 208 To 120 -Volt Service

d. 3-Phase, 3-Wire Delta-Connected Transformer, 480-Volt Service.

e. 3-Phase, 4-Wire Wye-Connected Transformer 480 To 277-Volt Service.

f. 3-Phase, 4-Wire Delta-Connected Transformer, 120 To 208 To 240-Volt Service.

Figure 5. Transformer Secondary Connections and System Grounding.

Systems with delta-connected secondaries may also be grounded through a grounding transformer. This provides a system ground that is not directly connected to one of the phases.

The major advantage of system grounding is the ease with which ground faults may be located in the system. If a ground fault occurs in a system without grounding, an unbalanced current is present in one of the phases. If this current is much smaller than the phase current, (and it often is), it is difficult to detect. In grounded systems, ground fault detectors in the ground line can detect even small ground currents. This is because, under normal operating conditions, the ground current is very small or zero.

The system may be connected to ground directly or through resistance. The direct connection is called solid grounding and is used on most low-voltage systems. This systems allows large ground currents for the operation of single-phase sections of the system and for ground fault detection in other parts. A low resistance in the ground connection reduces the ground fault current, but allows a current high enough to operate protective relays. Low-resistance grounding is used mainly in medium-voltage systems.

In high-resistance grounding, the resistance is chosen to limit the ground fault current to a low value, usually less than 0.1% of the short-circuit fault current. This is usually in the range of 1 to 10 amps. This current indicates the presence of a ground fault, but is not large enough to require immediate system shutdown. This grounding system is used in low-voltage systems that require high reliability. In low-voltage systems, an automatic shutdown due to a ground fault could cause equipment or product loss. Typical examples are paper mills and textile plants — where even a momentary interruption of power on high-speed equipment causes a major shutdown. Resistance grounding is limited to three-phase operation and cannot be used if the system is to power single-phase equipment.

CIRCUIT PROTECTION DEVICES

Two distinct types of circuit protection are required in all-electrical delivery systems. One overload is moderate, capable of damaging the circuit if it persists – but not dangerous for a short time. The other overload is a large current surge, such as a phase-to-phase short, that can cause major damage in a fraction of a second. Damage from these two types of overload may be avoided by a single device – or by two separate protective devices.

In selecting protective devices, five factors must be considered.

1. Voltage rating of the system. The protective device must be capable of interrupting the rated voltage.
2. Rated load current of the equipment. The device must conduct the rated load current without interruption.
3. Load type, whether steady or fluctuating – or subject to surges, such as motor-starting. The protective devices for circuits with normal surges must conduct those surges without opening – but must open at the same current levels if the over-current persists.
4. Short-circuit current of the system. Many devices that can interrupt moderate overloads cannot interrupt short-circuit currents that may be hundreds of times greater than the normal circuit current. They must be used in series with other devices that can interrupt the short-circuit current.
5. Coordination with other protective devices. All circuits will contain several protective devices. These must be timed to operate in a particular sequence. Thus, delay time between the fault and the opening of the circuit protection device is an important consideration.

FUSES

Fuses are the least expensive protective devices. Several fuse types are widely-used. Figure 6 shows three common fuse types.

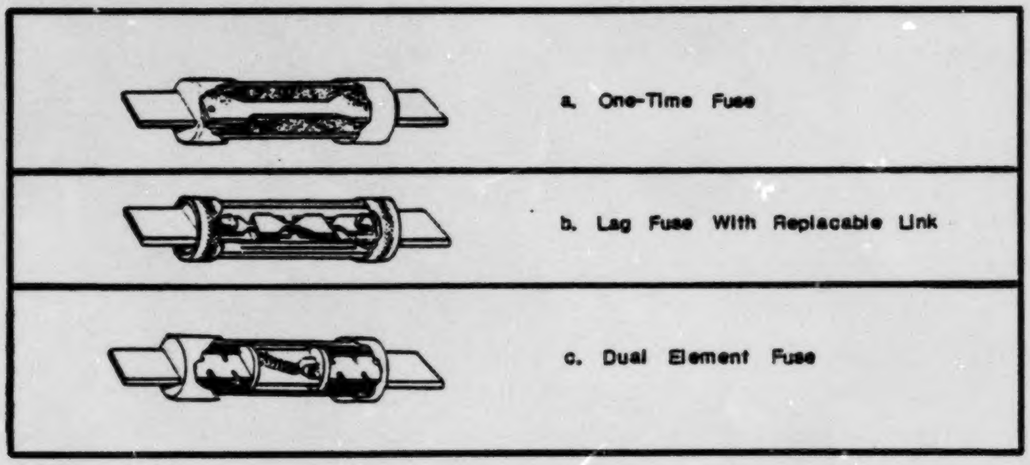


Figure 6. Fuses for 600 V and below.

One-time fuses (Figure 6a) have the shortest delay time. They are the simplest and least expensive fuses, but they are not suited for applications in circuits with brief, but heavy, overloads. A one-time fuse that would withstand the starting surge of a motor would be rated too high to provide protection from moderate overloads.

Lag fuses (Figure 6b) have longer time delays to allow for momentary surges. The wider portions of the fuse element act as heat sinks for the narrower portions and delay blowing during the surge. If a large current surge occurs, the heat cannot be conducted away fast enough and the fuse blows.

Persistent moderate overloads heat the whole fuse element until it blows. The fuses have replaceable links and are commonly used in motor circuits.

Dual element fuses (Figure 6c) contain two elements in series. A time-delay element on each end does not respond to surges, but will open if moderate overloads persist. A fast-acting element in the center will carry moderate overloads without blowing — but will open quickly in case of a large current surge. This fuse provides both types of circuit protection.

Special current-limiting fuses (not shown) are designed to open very quickly in case of a very large current surge resulting from a short-circuit. They are used in series with other protective devices, usually circuit breakers, when these devices are incapable of interrupting the short-circuit current before the circuit is damaged. Current-limiting fuses are commonly installed in both primary substations and load centers.

Fuses are always installed in circuits with either circuit breakers or disconnect switches before the fuse. When the fuse blows, the disconnect device is used to de-energize the circuit in front of the fuse; thus, the fuse can be safely replaced with no voltage hazard. Fuses should never be installed in a circuit before the disconnect device.

CIRCUIT BREAKERS

Primary substations may incorporate oil or air-blast circuit breakers described in Module PI-02, "Electrical Power Transmission and Distribution." At voltages of 13.8 kV and below, two types of air circuit breakers may be used – depending on current and voltage.

At voltages up to 600 V and current up to 800 A, molded-case air circuit breakers may be used. These devices are avilable in a wide range of sizes and in several configurations.

Figure 7 illustrates the construction and operation of a typical air circuit breaker. This device contains two protective elements. A bimetallic thermal element is heated by current flowing through the device. It does not respond to momentary overloads, but opens if moderate overloads persist. The magnetic element does not respond to moderate overloads, but opens quickly if a short-circuit occurs. Most molded-case circuit breakers are of this type, although some contain only one element or the other. These breakers are also commonly used in residential distribution systems.

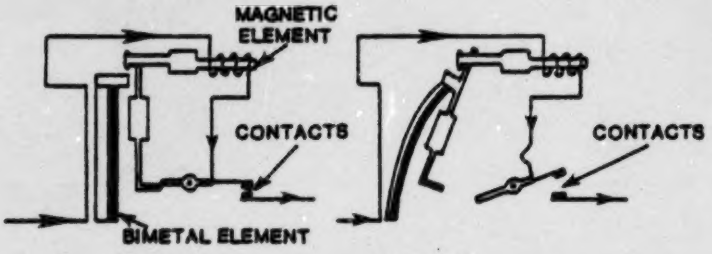
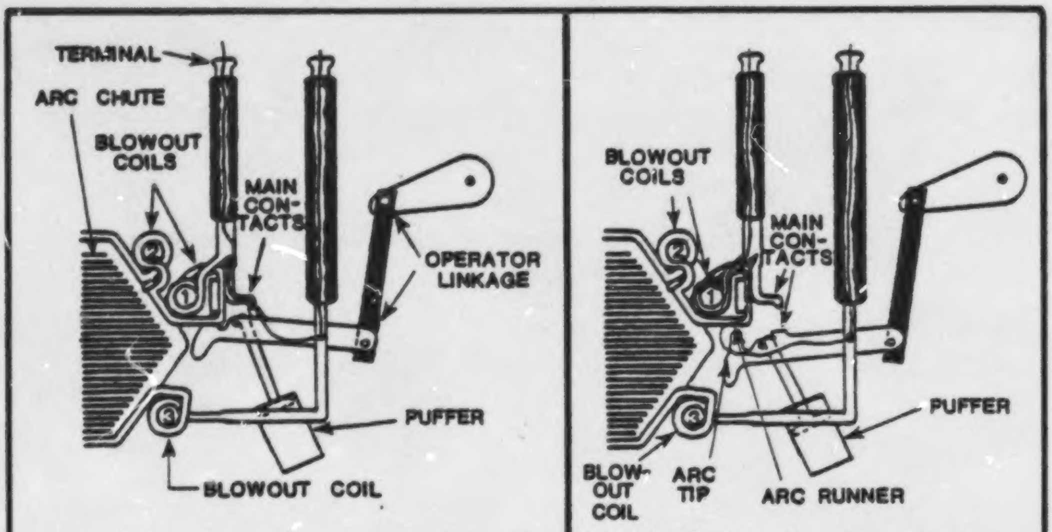


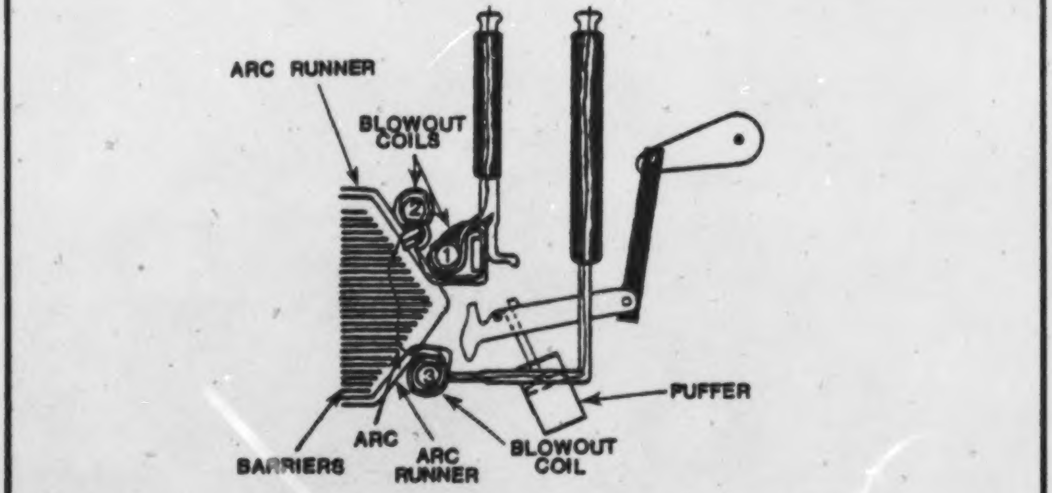
Figure 7. Thermal-Magnetic Molded-Case Circuit Breaker.

Figure 8 shows the construction and operation of an air-magnetic circuit breaker. This type breaker is available in voltage ratings up to 13.8 kV. Larger models carry rated currents of 4,000 A and can interrupt currents as high as 60,000 A.


TERMINAL
ARC CHUTE
BLOWOUT COILS
MAIN CON-TACTS
OPERATOR LINKAGE
①
②
③
PUFFER
BLOWOUT COIL
BLOWOUT COILS
MAIN CON-TACTS
PUFFER
BLOW-OUT COIL
ARC TIP
ARC RUNNER

a. Closed Position of Breaker With Current Flowing Through the Studs and the Main Contacts

b. Starting to Open. Main Contacts Part and the Current Shifts to Arcing Contacts and First Coil


ARC RUNNER
BLOWOUT COILS
①
②
③
PUFFER
BARRIERS
ARC
ARC RUNNER
BLOWOUT COIL

c. Interruption Occurs as Arc is Driven Against Arc Splitters by Magnetic Action of Blowout Coils

Figure 8. Operation of an Air Circuit Breaker.

As the contacts of the air-magnetic breaker open, an arc is formed. Current flows through this arc and through the first blowout coil. The magnetic field produced by this coil exerts a force on the electrons and causes the arc to expand into the arc chute. As the arc expands, the current path includes additional blowout coils. The arc chute contains arc splitters similar to the air-blast circuit breakers. Larger models also include a cylinder called a puffer that directs a momentary puff of air into the arc chute to assist in quenching the arc. Air-magnetic circuit breakers may be actuated by an internal current transformer or by a remote relay.

RELAYS

Relays are used with current or voltage transformers to operate circuit breakers from remote locations. Many types are available for a wide range of applications. Three common types are discussed here.

Figure 9 is a plunger-type relay, consisting of a coil with a movable plunger. Adjustments are usually provided to set the relay to close at a desired current. When that current is reached, the plunger moves upward, closing the stationary contacts. Dash pots may be added to provide a time delay. A dash pot is a piston

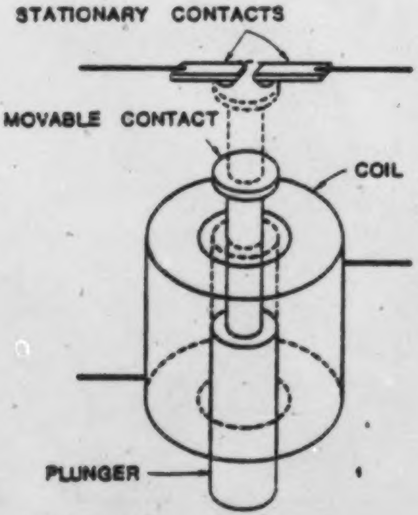


Figure 9. Plunger-Type Relay.

with a hole that moves inside a cylinder that is filled with air or liquid. The dash pot's resistance slows the action of the relay.

Figure 10 is a time-delay induction disk relay. The operating mechanism is very similar to that of a watt-hour meter. Current-carrying coils induce eddy currents in an aluminum disk. The magnetic fields of these currents interact with the fields of the stationary coils to produce a torque on the disk, causing the movable contact to rotate against the stationary contacts. These relays have adjustments for operating current and time-delay. Both this relay and the plunger-type relay are used for overcurrent and overvoltage protection. Some relays, called definite time relays,

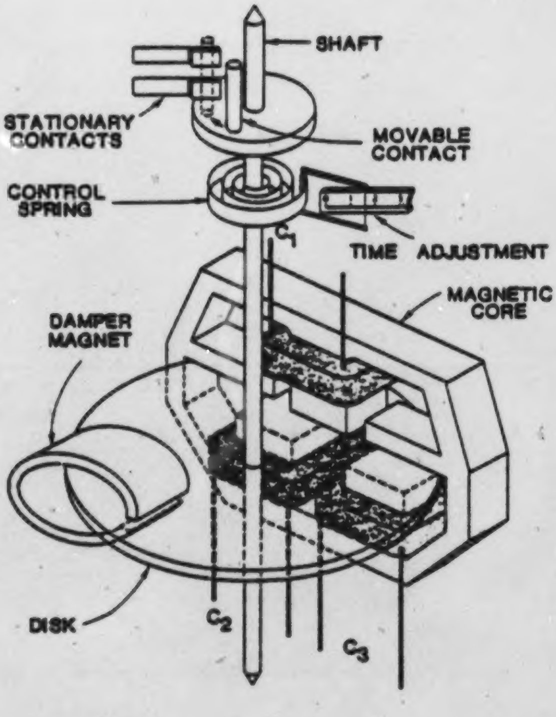

SHAFT
STATIONARY CONTACTS
MOVABLE CONTACT
CONTROL SPRING
C_1
TIME ADJUSTMENT
MAGNETIC CORE
DAMPER MAGNET
DISK
C_2
C_3

Figure 10. Time-Delay Induction Disk Relay.

are designed to close after a set delay for any value of overcurrent. Inverse time relays are more common and close faster for higher currents.

Figure 11 is a balanced beam differential relay. This relay compares two input signals and closes if the currents are out of balance. The application of a differential relay for transformer ground fault detection is shown in Figure 12. A current transformer on the primary side of the transformer is connected to the operating coil. The restraining coil receives current from a current transformer on the secondary side of the power transformer.

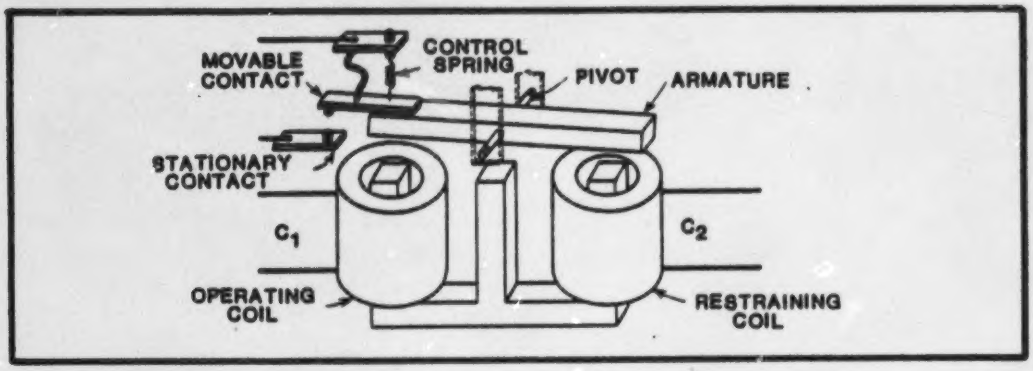

MOVABLE CONTACT
CONTROL SPRING
PIVOT
ARMATURE
STATIONARY CONTACT
C1
C2
OPERATING COIL
RESTRAINING COIL

Figure 11. Balanced Beam Differential Relay.

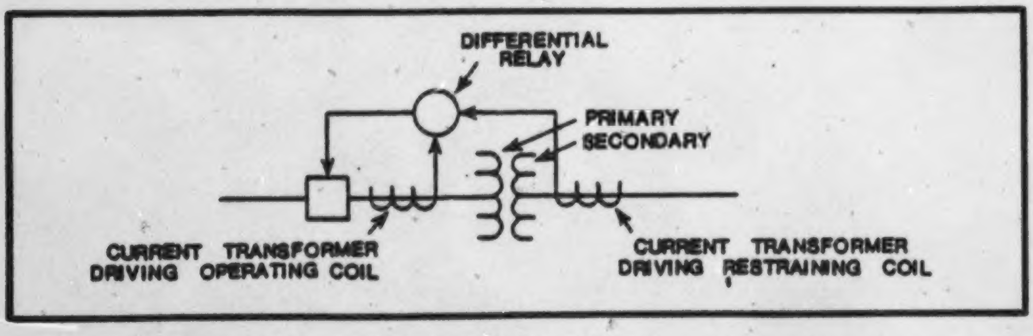

DIFFERENTIAL RELAY
PRIMARY
SECONDARY
CURRENT TRANSFORMER DRIVING OPERATING COIL
CURRENT TRANSFORMER DRIVING RESTRAINING COIL

Figure 12. Differential Relay for Transformer Fault Detection.

During normal transformer operation, the restraining coil holds the relay open. If a fault occurs in the transformer, the primary current increases and the secondary current decreases or remains the same. The operating coil of the relay then receives more current and the relay closes, tripping the circuit breaker and disconnecting the power transformer from the power line.

OVERCURRENT PROTECTION

The most common application of relays and circuit breakers is overcurrent protection. All electrical power distribution systems have more than one overcurrent protection device in series, as shown in Figure 13. Two types of time sequences may be used to trip these protective devices.

In a selective tripping arrangement, only one relay is expected to open in case of a fault. Each breaker or fuse in the system is capable of interrupting the short-circuit current of the circuit. If a fault occurs past circuit breaker C, this circuit breaker will open to isolate the fault. In selective tripping, the breaker nearest the load operates the fastest. Each successive breaker going back

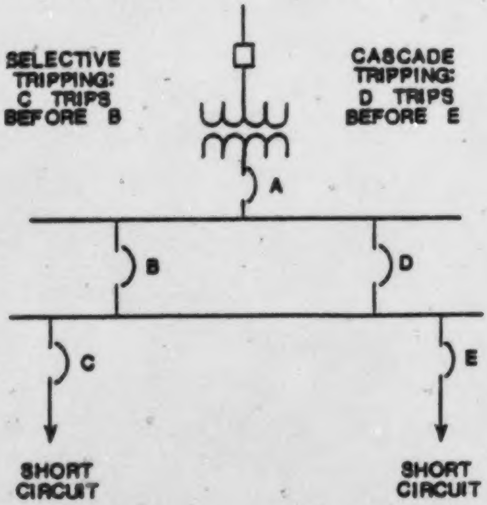

SELECTIVE TRIPPING: C TRIPS BEFORE B
CASCADE TRIPPING: D TRIPS BEFORE E
A
B
D
C
E
SHORT CIRCUIT
SHORT CIRCUIT

Figure 13. Selective and Cascade Tripping of Circuit Breakers.

toward the primary substation has a longer time delay. This is the preferred relay scheme for most applications because it isolates the fault with minimum disturbance to the rest of the system.

In a cascade system, the length of time delay for short-circuits is reversed. Breaker E opens to protect the circuit from moderate overloads, but is not capable of interrupting the short-circuit current of the system. In case of a large current surge, breaker D operates more quickly than E. This reduces the cost of the breakers -- but results in a power loss in a larger portion of the system if a ground fault occurs.

SUMMARY

Industrial electrical power distribution systems usually include a primary substation and several secondary substations, or load centers. Primary distribution is accomplished at the highest voltage feasible in order to reduce current and, thus, reduce losses and voltage drop in the lines under load. The most common distribution voltage is 480Y/277 V. This system provides efficient power distribution for moderate-size, three-phase motors and the 277-V, single-phase service provided may be used for fluorescent lighting. Plants with higher power needs may use higher voltages, and smaller plants may use 240 V or 208 V.

Radial distribution schemes are the most common, but systems incorporating multiple branches and networks may be used to increase reliability. In all cases, circuit protection must be provided for both moderate overloads and high-current surges resulting from short-circuits. This is accomplished by the use of fuses and air circuit breakers.

Equipment frames and conduits are grounded for protection of personnel. In most low voltage systems, the power system is grounded. This provides more protection of equipment and circuits by making the detection of ground faults easier.

EXERCISES

1. Draw and label diagrams of the following types of primary substations:
    a. Typical radial distribution station
    b. Radial station with twin feeds from two power lines
    c. Primary loop with a secondary tie circuit breaker
    d. Twin feed with a secondary tie
2. Draw and label diagrams of the following types of secondary substations:
    a. Radial distribution
    b. Secondary selective
    c. Primary selective
    d. Network
3. Draw and label the transformer secondary connections of a 480Y/277 V system with a solid ground.
4. Explain the reasons for the popularity of the 480Y/277 V system in industrial plants.
5. Describe circumstances in which a lower voltage distribution system is preferred.
6. Explain the following terms:
    a. System grounding
    b. Equipment grounding
    c. Solid grounding
    d. Resistance grounding
7. Explain the advantage of resistance grounding.
8. List and explain the five factors to be considered when selecting circuit protection devices.
9. Describe the characteristics and applications of the following types of fuses:
    a. Lag
    b. One-time

   - c. Current-limiting
   - d. Dual element

10. Describe the construction, operation, and voltage ranges of the following types of circuit breakers:
    - a. Air-magnetic circuit breakers
    - b. Molded-case circuit breakers
11. Describe the construction and operation of the following types of circuit breakers:
    - a. Plunger
    - b. Time-delay induction disk
    - c. Balanced beam differential
12. Explain the difference in selective tripping and cascade tripping of circuit protective devices.

LABORATORY MATERIALS

Spiral notebook or clipboard
Pen or pencil

LABORATORY PROCEDURES

The laboratory for this module consists of a field trip to an industrial power distribution system. The purpose is to observe the application of equipment and techniques described in this module in an industrial setting. Areas to be examined include primary and secondary substations, protective devices and systems, grounding methods, and location and types of conductors.

1. Observe the primary substation during the familiarization tour. Sketch all components of the station and

list the specification of each component. Include the current and voltage-carrying capabilities of all protective devices and the current-interrupting capabilities and time-delays of all circuit breakers. Record all data in the field notebook.

2. Observe and sketch the components and arrangement of secondary substations. Include all equipment specifications and connections.
3. Describe the type and layout of conductors leading from the primary substation to the load centers.
4. Describe the type and layout of conductors leading from the load centers to the equipment served.
5. Describe the grounding system used and the methods used to detect ground faults.
6. After the completion of the field trip, prepare a schematic diagram of the power distribution system. Include the voltages and rated currents throughout the system and the equipment served by each branch circuit. Discuss the following topics as they apply to this system and describe how they might be improved:
   a. Reliability
   b. Efficiency
   c. Circuit protection

DATA TABLES

Include all field notes in the field notebook or folder and turn them in with your completed report.

REFERENCES

"In-Plant Electrical Distribution - A Special Report." Power (James O'Connor, editor). New York: 1965.

Rowan, W.O. Electrical Power Substations, Part 2. Scranton, PA: Intext, Inc., 1973.

TPC Training Systems. Three-Phase Systems. Barrington, IL: Technical Publishing Co., 1974.

TPC Training Systems. Electrical Protective Devices. Barrington, IL: Technical Publishing Co., 1972.

TEST

Please circle the appropriate answer.

1. In comparing a 480-V and 240-V distribution system for the same load, the higher voltage system ...
    a. operates at lower current.
    b. has lower voltage drops along the distribution lines.
    c. provides 120-V, single-phase for the operation of hand tools.
    d. All of the above are correct.
    e. Only a and b are true.
    f. Only a and c are true.

2. In primary distribution substations, the major component immediately preceding the large air circuit breaker is usually the ...
    a. disconnect switch.
    b. transformer.
    c. oil circuit breaker.
    d. high-voltage line connection.
    e. voltage regulator.

3. A tie circuit breaker on the main secondary distribution bus ...
    a. is normally closed, so two transformers in parallel supply power to the entire load.
    b. is usually an oil circuit breaker.
    c. may be closed to power the entire load from one transformer if the other fails.
    d. is included in most distribution systems, but may be eliminated.
    e. Only c and d are true.

4. A secondary selective load center includes ...
   a. two step-down transformers.
   b. a normally-open tie circuit breaker in the secondary distribution bus.
   c. air circuit breakers on both the transformer primaries and secondaries.
   d. Only a and b are true.
   e. Only b and c are true.

5. A network distribution system with multiple feeders ...
   a. is the most common distribution system in industry.
   b. is less expensive than the primary selective system, but provides lower reliability.
   c. requires at least two transformers in each load center.
   d. reduces the need for circuit protective devices.
   e. None of the above are correct.

6. All industrial electrical distribution systems include ...
   a. solid grounding.
   b. equipment grounding.
   c. system grounding.
   d. equipment and system grounding.
   e. resistive or solid grounding.

7. A 480Y/277 V distribution system ...
   a. has a phase-to-phase voltage of 277 V.
   b. has a phase-to-ground voltage of 480 V.
   c. requires a solid ground for the operation of fluorescent lights.
   d. All of the above are correct.
   e. None of the above are correct.

8. A current-limiting fuse ...
   a. provides protection from both moderate overloads of long duration and short-circuit currents.
   b. is used in series with air-breakers when the breaker cannot interrupt the short circuit current.
   c. has replaceable fuse links.
   d. is used in series with air breakers when the breaker cannot respond to long-duration moderate overloads.
   e. None of the above are correct.

9. Which of the following fuses is never used in motor circuits?
   a. Lag
   b. Dual element
   c. One-time
   d. Current-limiting
   e. All may be used.

10. Molded-case circuit breakers ...
    a. usually protect against both moderate overloads and short-circuits.
    b. can be used only at voltages of 480 V and below.
    c. are less common than air-magnetic breakers.
    d. Both a and b are true.
    e. Both a and c are true.

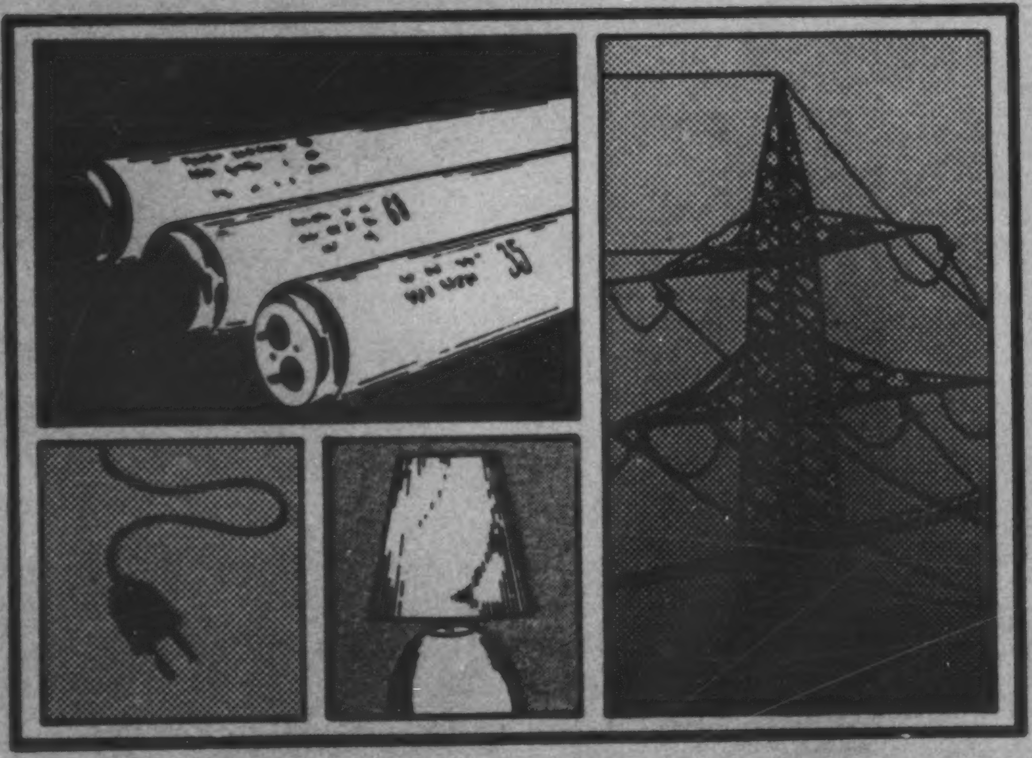
11. Time-delay induction disk relays ...
    a. are used for overcurrent protection.
    b. are less complex than plunger relays.
    c. do not require current transformers.
    d. usually have no adjustments for current trip level or time-delay.
    e. Both a and d are true.

12. Air-magnetic circuit breakers ...
   a. are available in voltages up to 35 kV.
   b. depend upon a blast of compressed air, as well as magnetic blowout coils for their operation.
   c. are the most common types in industrial and residential switch boxes.
   d. must be used in series with current-limiting fuses.
   e. None of the above are correct.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-04

RESIDENTIAL ELECTRICAL DISTRIBUTION

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

This module, "Residential Electrical Distribution," describes the characteristics of safe wiring systems based on the National Electric Code and includes additional information on the selection of wire sizes for efficient operation.

The National Electric Code is a complete listing of all wiring practices that are accepted as safe. Obviously, this listing is lengthy and cannot be discussed in detail in this module. The intent of this discussion is to familiarize the student with general requirements of the code and common practices used in residential installations.

Topics include circuit protection, circuit grounding, circuit devices and their installation, wire sizes and types, and acceptable wiring practices.

In the laboratory, the student will construct a residential branch circuit in accordance with the requirements of the National Electric Code.

PREREQUISITES

The student should have completed Module PI-03, "Industrial Electrical Distribution."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe the intent and purposes of the National Electric Code and Underwriters Laboratory.

2. Draw circuits containing the following switch types and explain the operation of each:
   a. Single-pole switch
   b. Double-pole switch
   c. Three-way switch
   d. Four-way switch
3. Describe the color code of the terminals of outlets.
4. Describe the appearance and application of the following types of fuses in residential circuits:
   a. Edison-base fuses
   b. Type S screw-in fuses
   c. Type SC cartridge fuses
5. Explain the meaning of the following symbols in the designation of wire types:
   a. T-coded wire
   b. H-coded wire
   c. W-coded wire
   d. N-coded wire
   e. R-coded wire
6. Explain the importance of voltage drops in residential distribution systems. Delineate drops in voltage that are considered acceptable.
7. Identify the composition and uses of common cable types, given their identification numbers.
8. Describe the general requirements for conduit and boxes used in residential electrical systems.
9. Explain the color codes used for wires in residential systems and the uses of wires of each color.
10. Explain the characteristics of the grounded conductor of residential systems and the characteristics of conductors used for equipment and component grounding.

11. Describe the characteristics of acceptable splices and connections.

12. Draw circuit diagrams showing the connections and colors of conductors in the following circuits:
    a. Single-pole switch controlling an outlet with the source at the switch.
    b. Single-pole switch controlling an outlet with the source at the outlet.
    c. Two three-way switches controlling an outlet with the source at the outlet.
    d. Two three-way switches controlling an outlet with the source at the first switch.

13. In the laboratory, construct a residential branch circuit consisting of two three-way switches controlling an outlet.

CODES AND TESTING LABORATORIES

Residential electrical distribution systems are required to meet certain standards for safety and must be approved by local authorities. Such approval is usually based on the National Electric Code and the listing of circuit components by Underwriters Laboratory. Approval assures the safety of the system but does not guarantee the system's efficiency.

NATIONAL ELECTRIC CODE

The National Electric Code (NEC) is a list of rules and regulations that establishes safe methods of installing electrical materials. The NEC is published by the National Fire Protection Association and is the accepted standard governing all electrical work. The code is intended to assure that the installation is free of both electrical and fire hazards. It does not assure that the installation will be efficient, convenient, or adequate for the purposes intended. These tasks are the responsibility of the designer.

The NEC is not the law. It becomes law only when it is adopted as such by local governmental enforcing authorities. Almost every locality has an electrical code. Some adopt the NEC, while other state and local authorities prohibit some practices that are acceptable in the NEC or impose additional restrictions. The practices described in this module are in accordance with the National Electric Code.

To be sure that all these practices are acceptable in any locality, it is necessary to check with local authorities.

The NEC is revised and updated each year. To ensure compliance, the most recent edition of the code should be consulted. The National Electric Code is available from the National Fire Protection Association, 470 Atlantic Ave., Boston, MA 02210.

UNDERWRITERS LABORATORY

The approval of all installations is the responsibility of the authority having jurisdiction in the particular locality. Materials used are usually approved on the basis of listing by an accepted testing laboratory. Several such laboratories exist, but by far the most widely accepted is Underwriters Laboratory, Inc.

Materials and equipment items are tested by the laboratory. Items that pass the tests are listed as safe and bear the words "listed by Underwriters Laboratory" or the symbol "UL." The laboratory does not approve items and does not certify them as to efficiency, convenience, or durability. A UL listing certifies only that the item is safe – if used as intended – and presents no electrical or fire hazards if in proper working condition.

Two similar items of unequal quality may be listed if each presents no hazards. UL does not list any products that are in violation of NEC requirements. Many products are not listed by UL; these products should not be used. Moreover, most inspecting authorities will not approve items that are not listed.

CIRCUIT DEVICES

Circuit devices include switches and outlets. Types of toggle switches include the single-pole, double-pole, three-way, grounded duplex outlet, and the screw socket.

SWITCHES

By far, the most common type of switch in residential circuits is the familiar toggle switch used to control lighting circuits, outlets, and certain built-in appliances. While all of these switches have the same external appearance, four distinct types are used. The internal connections of these switches and their applications in circuits are shown in Figure 1.

The single-pole switch shown in Figure 1a is the most common switch. It has two terminals that are connected in the ON position and disconnected in the OFF position. This type switch is used to control most 120-V circuits that have only one switch. It is always installed in the hot conductor. Single-pole switches are never installed in the neutral (ground potential) conductor.

Figure 1b shows a double-pole switch that disconnects both conductors leading to a load. This switch is employed only when neither of the conductors is at ground potential. This type switch is almost never used in 120-V circuits but is common is 240-V circuits, since neither of the conductors is grounded. The words ON and OFF appear on the handle of both single-pole and double-pole switches.

The switch shown in Figure 1c is called a three-way switch because it has three terminals and three conductors

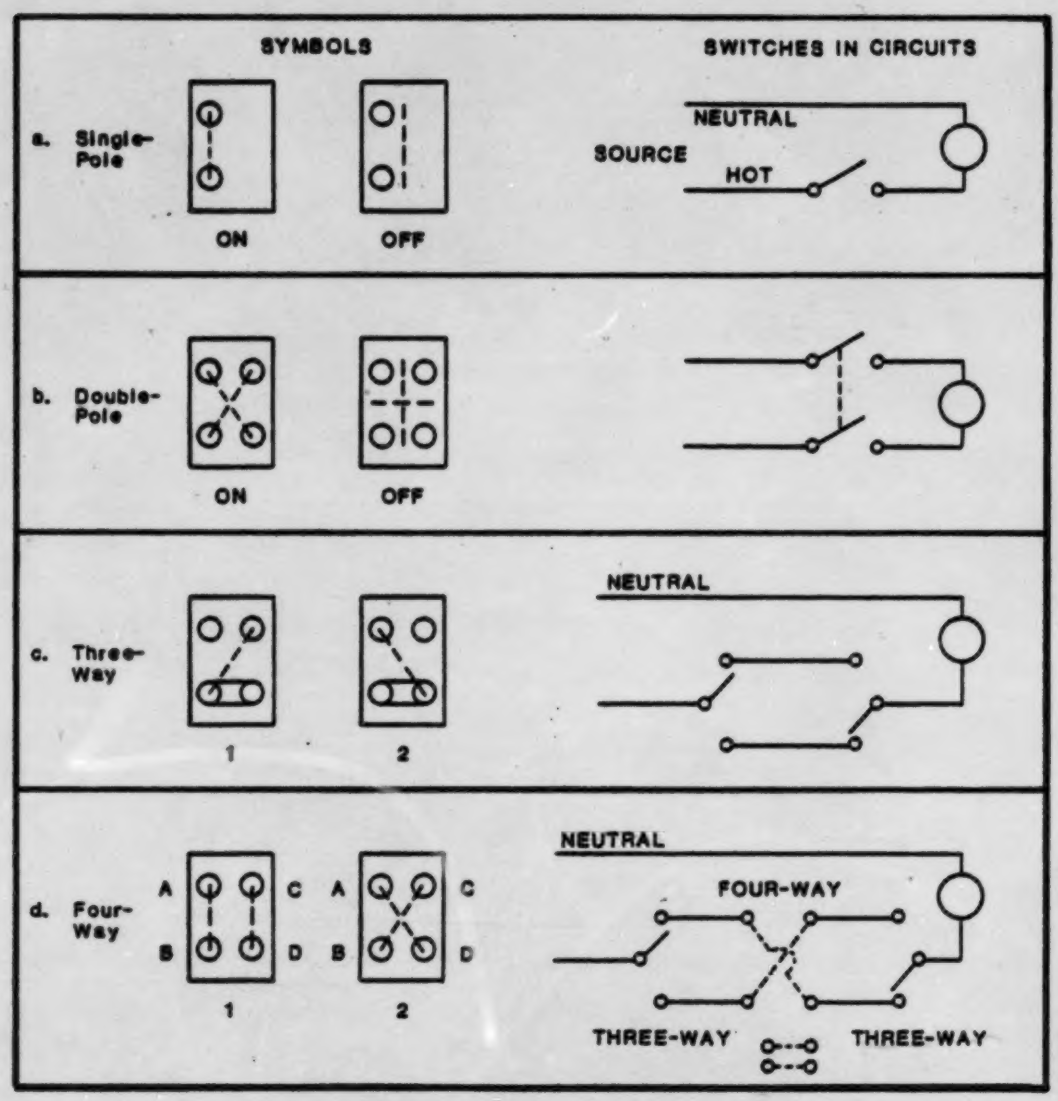

SYMBOLS
SWITCHES IN CIRCUITS
a. Single-Pole
ON
OFF
NEUTRAL
SOURCE
HOT
b. Double-Pole
ON
OFF
c. Three-Way
1
2
NEUTRAL
d. Four-Way
A
B
C
D
A
B
C
D
1
2
NEUTRAL
FOUR-WAY
THREE-WAY
THREE-WAY

Figure 1. Switches.

connected to it. The name is somewhat misleading, since it implies that the switch has three positions or can be used to control a circuit from three locations. This is not the case. This switch is actually a double-throw switch that connects one conductor to either of two other conductors.

Such switches are used to control a circuit from two separate locations, as shown in the circuit diagram. In this circuit, either switch can turn the circuit ON or OFF regardless of the position of the other switch. The position of the terminals varies with manufacturers. In most cases, the terminal connected to the movable portion of the switch is a dark or oxidized color (for identification). Three-way switches are used only in the hot conductor, and an incorrect connection will make the switch inoperative (either ON or OFF all the time) but will present no hazard.

The four-way switch shown in Figure 1d has four terminals like the double-pole switch, but like the three-way switch, the words OFF and ON do not appear on the handle. This switch connects either teminals A to B and C to D or A to D and B to C. It is used with three-way switches when a circuit is to be controlled from three locations, as shown in the circuit diagram.

Additional four-way switches may be added between the two three-way switches for more control locations. The location and identification schemes for four-way switches vary with manufacturers, but there is no hazard involved in an incorrect connection. If the terminal arrangement is unknown, trial and error may be used until the circuit functions properly.

In addition to the terminals indicated in Figure 1, all new switches have a terminal (that is color-keyed green) for grounding the switch mechanism (for safety). This terminal is always connected to the system ground. However, some older models may not have this terminal.

OUTLETS

An outlet is defined as "any point at which the electrical energy is taken from the wiring system for application." Figure 2 shows a common grounded duplex outlet. The two vertical slots in the outlet carry the current. The rounded lower opening in the socket is for a ground connection and normally does not carry current. It is connected to the green ground terminal that is connected to the system ground. As explained previously, many older outlets do not include the ground connection. When such an older outlet is replaced, it should be replaced with a grounded outlet if – and only if – the ground terminal can be connected to the system ground.

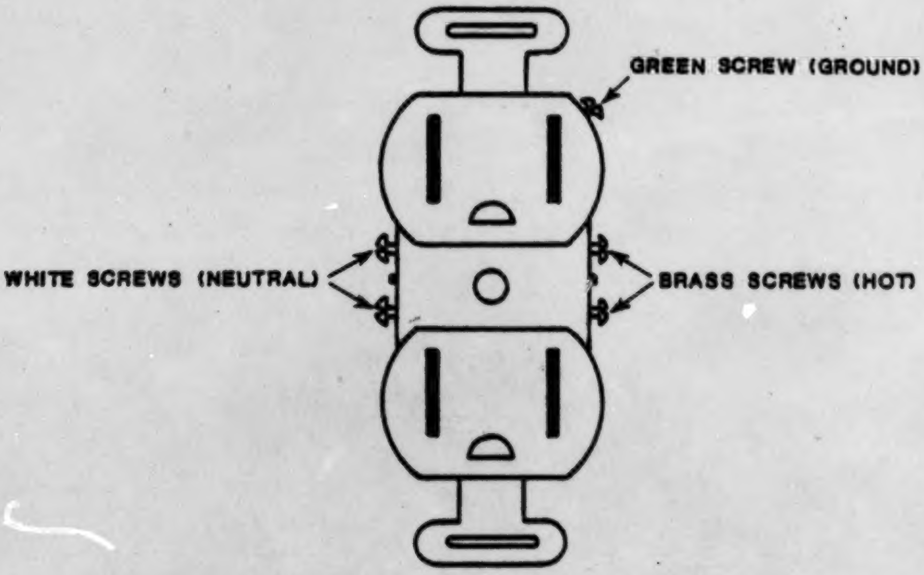


Figure 2. Grounded Duplex Outlet.

The current-carrying conductors of the circuit are connected to the terminals on the side of the outlet. The hot (black) wire is connected to the brass screws. The neutral (white) wire is connected to the screws that are plated with a silver or whitish metal.

Most outlets have two terminals on each side so that wires may be run from one outlet to another. These terminals are usually connected internally. However, in some outlets, terminals are separated so that one portion of the outlet is wired directly to the power source, while the other is controlled by a switch.

Although not required by the NEC, it is common practice to mount the outlet with the ground opening at the top. When a power cord is plugged into an outlet only part way, the upper conductors are usually exposed. If the current-carrying conductors are on top, a metal object could fall across them and result in a short circuit. Placing the grounded conductor on top prevents this.

Another common outlet type is the screw socket used for incandescent lights. Screw socket outlets have terminals with color-coded screws like duplex outlets.

CIRCUIT PROTECTION

Circuit protection devices are required for the main service entrance and for each branch circuit in residential installations. NEC rules require that all electrical power be disconnectable by not more than six disconnect devices. Many local codes require that all power feed through a single main circuit breaker or fuse switch combination, and this is the more usual practice. The code also requires that not more than 42 overcurrent devices be contained in one panelboard. However, most residential distribution systems consist of considerably fewer circuits.

Circuit protection can consist of fuses or circuit breakers. Many older installations employ Edison-type fuses with screw bases that are compatible with an ordinary light bulb. These are available with ratings of 15, 20, 25, and 30 A. The code requires that fuses rated at 15 A have a hexagonal face or window. Larger sizes must have a round face or window. These fuses are permitted only in existing installations. Edison-type fuses are never installed in new systems.

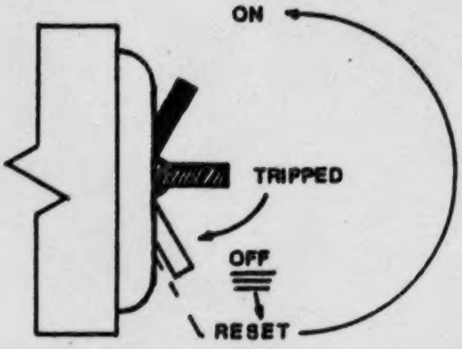
Type S fuses are also screw-in fuses, but the base of each rating is a different size to prevent replacement with the improper size fuse. These fuses screw into adaptors that are permanently installed in the Edison-type fuse holders. Type S fuses are available in the same amperage ratings with different adaptor and base sizes (except for 25 and 30 A fuses, which have the same size base).

Cartridge fuses are used for ratings of over 30 A and are also popular for lower ratings. These are available in several types, as described in Module PI-03, "Industrial Electrical Distribution." Cartridge fuses may be used in series with switches or in pull-out blocks that disconnect the circuit when the block is removed from its socket.

Branch circuits are often protected by type SC cartridge fuses in series with disconnect switches. In such cases, the disconnect switch always precedes the fuse in the circuit. The switch and fuse holder are often contained in a single housing with a neon bulb that lights to indicate a blown fuse. Like type S fuses, SC fuses have different sizes for different ratings; they cannot be interchanged.

The most common circuit protection devices in residential use are thermal-magnetic air circuit breakers, also described in Module PI-03. These breakers are mounted so that the handle is in the UP position when the circuit is complete, as shown in Figure 3. When the breaker trips, the handle moves to the MID position. To reset the breaker, it is necessary to move the handle downward past the OFF position and then back up to the ON position. These breakers are available in standard sizes from 15 to 200 A that are designed to snap into standard breaker boxes.

Figure 3. Operation of Single-Pole Circuit Breaker.



WIRES

Three types of wires have been used in residential installations. Aluminum and copper-clad aluminum wires have been used in the past and are still approved for a few applications. However, these wire types are fire hazards when used with standard connectors and are no longer installed in residential circuits. All new construction employs copper conductors. Only copper wires will be discussed in this module.

WIRE SIZES

Wire sizes are measured in terms of the American Wire Gauge. Figure 4 shows the diameters of the conductors of several common wire sizes. Even-numbered sizes from 4/0 (pronounced "four-naught") to 14 are commonly used in residential distribution systems. Larger sizes are standard for greater flexibility. The current rating depends, in part, upon the size of wire. However, current rating also depends upon the insulation type and method of installation, as shown in Table 1.

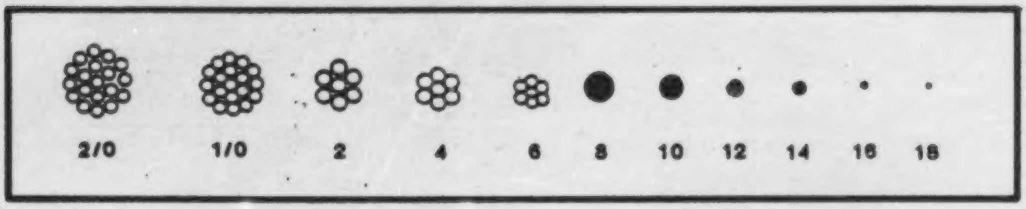


Figure 4. Actual Diameters of Typical Sizes of Electric Wires, Without Insulation.

TABLE 1. AMPACITY OF COPPER WIRES.

Wire Size	In conduit, cable, or buried directly in the earth		Single conductors in free air	
	Types T, TW, UF	Types RH, RHW, THW, USE	Types T, TW	Types RH, RHW, THW
	(A)	(B)	(C)	(D)
14	15	15	20	20
12	20	20	25	25
10	30	30	40	40
8	40	45	55	65
6	55	65	80	95
4	70	85	105	125
2	95	115	140	170
1/0	125	150	195	230
2/0	145	175	225	265
3/0	165	200	260	310

INSULATION TYPES

Many types of insulation are used on wires. Only common types are discussed here. Wire types used in residential applications are rated for 600 V. The current rating of a wire is proportional to the insulation's resistance to heat. This is because it is impossible for an electric current to flow through a wire without heating the wire. The heat of the wire can damage the wire's insulation.

Each wire type is also rated by the maximum temperature that the wire can withstand. Ratings are from 60°C (140°F) to 90°C (194°F). These are the actual operating temperatures of the wires and not the ambient temperature. Wires with the symbols H or HH in their designation have rated temperatures of 75°C or greater. Those without these symbols are rated at 60°C.

The NEC defines three types of locations for the installation of wires. Locations include those that are dry, those that are damp, and those that are wet. Dry locations are not normally subject to moisture, such as interior wiring. Damp locations, such as basements, are partially protected but may be subject to dampness. Wet locations, such as underground cables, are subject to saturation with water. Wire types with the symbol W in their designation may be used in any location. Those without this symbol are used in dry locations only.

The most commonly used wires are types T, TH, and THW. These wires have thermoplastic insulation. Types THHN and THWN have plastic insulation with a nylon covering. The nylon provides better insulation and greater mechanical strength and results in a smaller diameter for the same conductor size than type T.

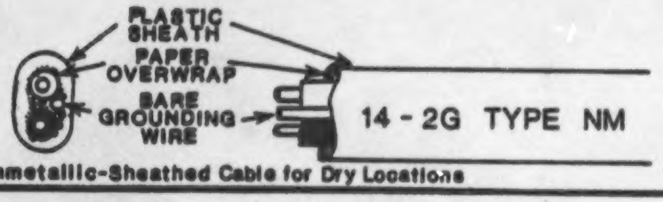
Wire types beginning with the symbol "X" have synthetic polymer insulation and require an even thinner layer of insulation. At one time, all wire for general use had rubber insulation designated by a beginning symbol, "R." Although this wire type is not popular today, some is still used. Several other types of insulation may also be used, but they are less common. The NEC contains tables specifying the conditions and limitations of use of all types of approved wire.

CABLES

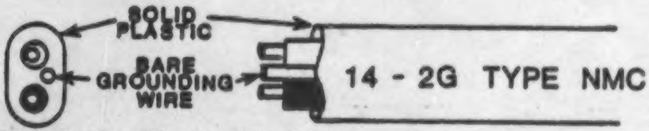
Two or more wires grouped together in a single covering are called a cable. Cables are popular for residential installations because they are usually easier to install than single wires and do not require the use of conduits for many applications.

Cable size is designated by the size and number of conductors it contains. Thus, a 12-3 cable has three size-12 conductors, each with individual insulation. Many cables contain two insulated current-carrying wires and a bare ground wire. A 10-2G cable has two insulated number 10 conductors and a bare number 10 ground wire.

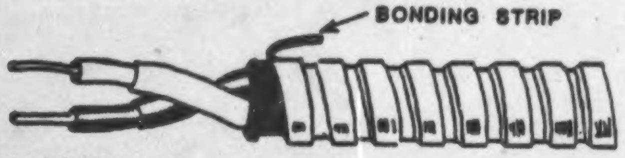
Figure 5 shows three common types of cable. Nonmetallic-sheathed cable, type NM (Figure 5a), contains two or three insulated conductors and may or may not have a bare


PLASTIC SHEATH
PAPER OVERWRAP
BARE GROUNDING WIRE
14 - 2G TYPE NM

a. Nonmetallic-Sheathed Cable for Dry Locations


SOLID PLASTIC
BARE GROUNDING WIRE
14 - 2G TYPE NMC

b. Nonmetallic-Sheathed Cable for Wet Locations


BONDING STRIP

c. Armored Cable

Figure 5. Cable Types.

ground. The wires are wrapped together with a paper wrap and covered with a plastic sheath. This is the most common type of cable for dry locations. It is used for most residential installations.

Type NMC (Figure 5b) is another nonmetallic-sheathed cable. This cable type has conductors that are embedded in a solid plastic covering. Nonmetallic-sheathed cable, type NMC, can be used in either dry or damp locations. It should not be used in wet locations or buried in the ground. Type UF underground feeder cable is similar in construction but may be buried or used in wet locations.

Armored cable (Figure 5c) has two or three conductors inside a spiral armor of galvanized steel. Each wire is wrapped in a layer of paper to protect it from abrasion by the metal armor. Armored cable does not contain a bare conductor, but a strip of aluminum is included inside the armor to improve the grounding capability. Armored cables are designated as types AC or ACT, although the trade symbol BX is also commonly used.

SELECTION OF PROPER WIRE SIZES

It might seem that the only consideration in selecting wire size is that the wire be rated to carry the current expected in the circuit. However, several other factors must be considered.

For continuous loads of three hours or more, the NEC limits the current of any conductor to 80% of the rated current.

When three of more current-carrying conductors are contained in a conduit — or when the ambient temperature exceeds 30°C (86°F) — the ampacity of the wires is also de-rated. Therefore, larger conductors may be required.

There is always some voltage drop along conductors in any distribution circuit. A voltage drop of 3% on the branch circuit conductors at the farthest outlet, or a total drop of 5% on both the feeder and branch conductors, is considered excessive and leads to inefficiencies. Not only is a significant amount of power consumed in heating the conductors, but most electrical devices are less efficient at lower voltages. If an electric motor is operated at a voltage 5% below its rated voltage, its power drops almost 10%. At a 10% voltage drop, the power drops by 19%. An incandescent bulb operated at 5% below its rated voltage produces 16% less light; at a voltage drop of 10%, the light output drops over 30%.

In residential circuits, the feeder lines are sized to produce a maximum voltage drop of 1 to 2%. Branch circuit conductors are normally sized to produce a maximum voltage drop of another 2%, and the total drop should not exceed 3%. For branch circuit lengths of more than about 50 feet, the conductor size must be increased to prevent an objectionable voltage drop.

The National Electric Code contains tables for determining the proper size of conductors for a variety of applications and branch circuit lengths.

BOXES AND CONDUIT

The following discussion centers on boxes, conduit, and sizing conduit and boxes.

BOXES

All circuit devices, such as switches, outlets, and breakers, must be mounted inside metal boxes. Figure 6 shows two switches mounted in a box with the cover plate removed. Such boxes are available in a large range of sizes and shapes.

These boxes have knock-outs of several standard sizes for connecting conduit or cable clamps. If the conductors leading to the box are contained in conduit, the conduit is electrically connected to the box to provide a ground.

If cables are used, cable clamps hold the cables securely in place and the ground conductor of the cable is connected to the box. In either case, the green grounding terminals of the components contained in the box are grounded to the box. Any knock-outs that have been opened but are not in use must be plugged with caps. All wire and cable connections are made inside such boxes. Wires to be connected in boxes must extend six inches into the box for easy connection.

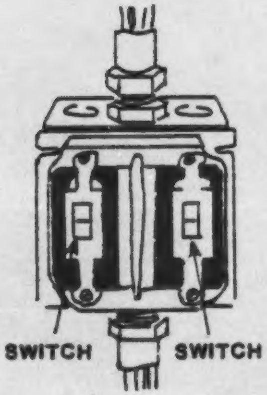


Figure 6. A Square Box with Two Switches.

TYPES OF CONDUIT

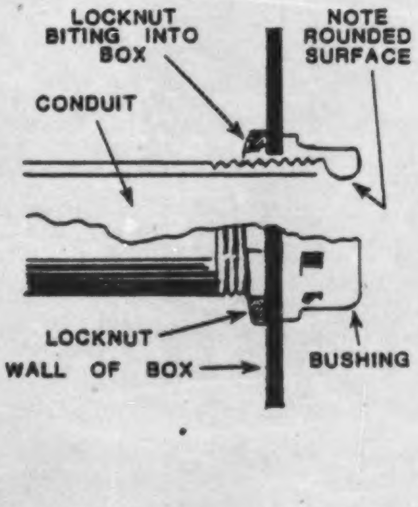
In many cases, the current-carrying conductors are contained inside metal conduits. Three types of conduit may be used.

Rigid metal conduit may be made of iron or aluminum. Iron and aluminum should never be used together because the junctions of dissimilar metals may result in corrosion and poor electrical contact. Rigid conduit is available in standard lengths of ten feet with threads on both ends.

When the conduit is cut to length, the inner surfaces must be reamed to prevent damage to the conductors. Conduit may be connected only with approved connectors. It must be firmly mounted within three feet of each outlet box. The code allows no more than the equivalent of four 90° bends (360° total) between outlet boxes or fittings. The restriction on bends is to limit the stress on the wire during this operation.

Conduit is installed first and the wires are pulled through it. The conduit is connected to the boxes by special connectors, as shown in Figure 7. A locknut on the outside

Figure 7. Cross Section Showing How a Locknut and Bushing are Used to Anchor Conduit to any Box or Cabinet.



of the box assures both mechanical strength and good electrical contact. The internal bushing has a rounded surface to prevent damage to the insulation of the wires. In all systems employing metal conduit, the conduit provides the electrical ground path.

Electrical metal tubing (EMT) is similar to conduit and may be used in most of the same applications. EMT has a thinner wall than rigid conduit and cannot be threaded. Connectors for EMT apply pressure to grip the tubing. Only connectors designed for that purpose may be used. All the rules applying to the use of rigid conduit also apply to the tubing.

Flexible metal conduit is similar in construction to the outer covering of armored cable. It is used where vibration exists — such as in connections to motors and machinery — and may also be used to make short radius bends that cannot be made with rigid conduit. Liquid-tight flexible conduit for wet locations has an outer plastic covering.

SIZING CONDUIT AND BOXES

The NEC allows conductors of different electrical circuits to occupy the same conduit as long as all voltages are 600 V or less. Thus, a single conduit may contain several circuits with several different voltages. In all cases, the conduit size is based on a maximum fill of 40%. This means that the total cross sectional area of the wires in the conduit, including insulation, cannot exceed 40% of the area of the conduit. In many cases, the conduit is oversized to allow for easier pulling of wires and to provide for the addition of future circuits.

Junction boxes are sized to prevent crowding of the conductors in the box. The size used depends on the number and size of conductors in the box. A conductor passing through a box without a splice or tap is counted as one conductor and each conductor that is tapped or spliced to another conductor is counted as one conductor. Tables specifying the sizes of boxes for various applications may be found in the NEC.

WIRING PRACTICES

The discussion about wiring practices that follows concerns color codes, grounding, splices and connections, and circuit connections.

COLOR CODES

Wire for residential use is color-coded for easy identification of individual wires when several conductors are bundled together. The following color combinations are commonly used when individual wires are placed together in a single conduit and for the individual conductors within cables:

- 2 wires – white, black
- 3 wires – white, black, red
- 4 wires – white, black, red, blue
- 5 wires – white, black, red, blue, yellow

Insulated grounding wires are always green (or green with a yellow stripe) and should be used for no other purpose.

GROUNDING

All residential electrical systems are grounded systems. (System and equipment grounding are discussed in Module PI-03, "Industrial Electrical Distribution.") In 120-V circuits, one of the conductors is always at ground potential. This conductor is grounded both at the distribution transformer and the service entrance. If the grounded wire is size 6 or smaller, it must be either white or gray throughout its length. If larger than number 6, it must have the same white or gray color, be painted white at each terminal, or be taped with white or gray tape at each terminal. The only exception to the use of the white wire as the grounded wire is in some switch loops as described later in this module.

The grounded wire is never interrupted by a circuit breaker, fuse, switch or other device. All grounded wires in a system are connected directly to the system ground.

Grounding wires for equipment and switch and outlet boxes are usually bare. If they are insulated, they must be either green or green with a yellow stripe. In systems employing conduit, the conduit acts as the grounding conductor. All outlets and switches in new construction must be connected to a continuous grounding system that is tied to earth ground.

SPLICES AND CONNECTIONS

All splices and connections in the system must be both mechanically and electrically secure. The emphasis is usually on mechanical strength, as this also assures good electrical connections.

Wires may be spliced, as shown in Figure 8. Splices must be contained in boxes where they are accessible and cannot be located inside conduit or cable runs. In all cases, the splice must be both electrically and mechanically secure without solder. Solder is applied only to prevent oxidation of the conductors. The conductor must be entirely covered with an insulation equivalent to that of the conductors. Plastic tape may be used, or the splice may be wrapped with rubber tape with a covering of friction tape.

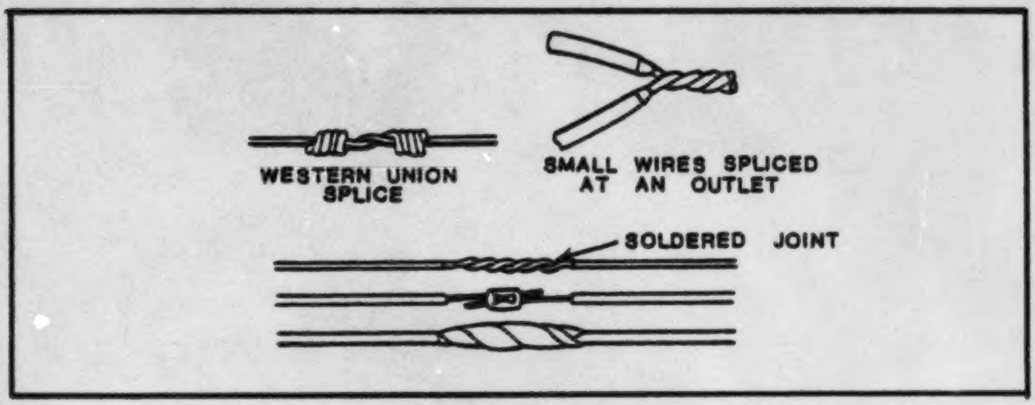


Figure 8. Splices and Joints Mechanically and Electrically Secure.

The most common way of connecting wires in residential systems is with wire nuts, as shown in Figure 9. These are plastic caps containing a threaded conductor or a spiral spring. The straight, bare ends of the conductors are held together and the wire nut is screwed onto them. Wire nuts are available in several sizes. The package containing

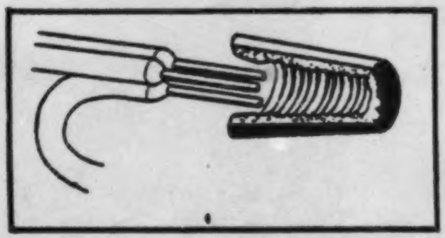


Figure 9. Wire Nut.

each size specifies the sizes and number of conductors for which that wire nut may be used.

Figure 10 shows how to connect conductors to terminals. Wire must be looped in the proper direction so that tightening the screw will tend to close the loop. Wire must extend at least two-thirds of the distance around the screw — but may not overlap itself. The bare conductor may not extend more than one-quarter inch from the screw. The insulation should be cut at an angle of about 60°, as shown in both Figures 9 and 10. The screw must be tightened until it grips the conductor securely. Wires may end at the terminal or be looped around one terminal and extend to another terminal.

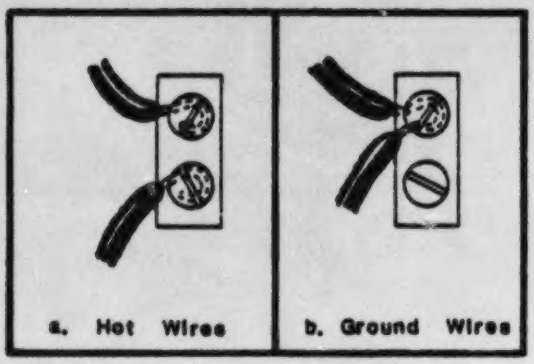


Figure 10. Connections of Wires to Terminals.

CIRCUIT CONNECTIONS

All circuit outlets must be connected with a white wire as the ground wire and some other color (usually black) as the hot conductor. Duplex outlets are usually made with two screws on each side so that wires can be run from one outlet to the next in the circuit. In such cases, hot wires may be connected to the terminals, as shown in Figure 10a. The ground wire may not be broken at the outlet. It may be connected as shown in Figure 10b.

A better way to connect the ground wire is shown in Figure 11a. This figure shows a duplex outlet served by two separate hot wires and a single ground wire. The circuit also includes other outlets. In all cases, the ground wire must be uninterrupted by any circuit devices. The connection shown in Figure 11b is forbidden.

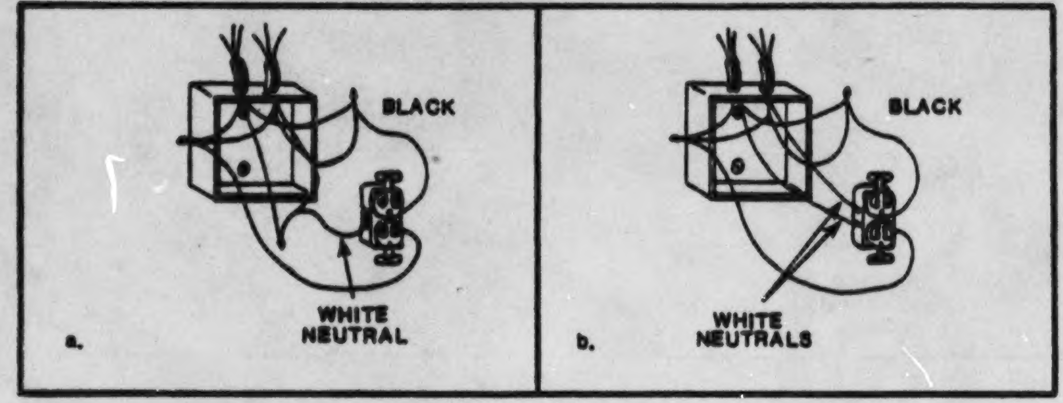


Figure 11. Connecting the Neutral in a Three-Wire Circuit.

The only case in which the ground wire may be any color other than white or gray is in switch loops. Figure 12 shows two methods of connecting switch loops containing a single switch and outlet.

If the switch is located at the source as shown in Figure 12a, it is installed in the black (hot) wire. The continuous white wire extends to the outlet. The hot wire is interrupted by the switch, but the ground wire is continuous.

Figure 12b shows the connection of this circuit when the light is at the source. The switch loop of this circuit contains a white wire that is not a ground wire. This is acceptable when cable is used for the switch loop. At the outlet, the ground wire is white and the hot wire (from the switch) is black.

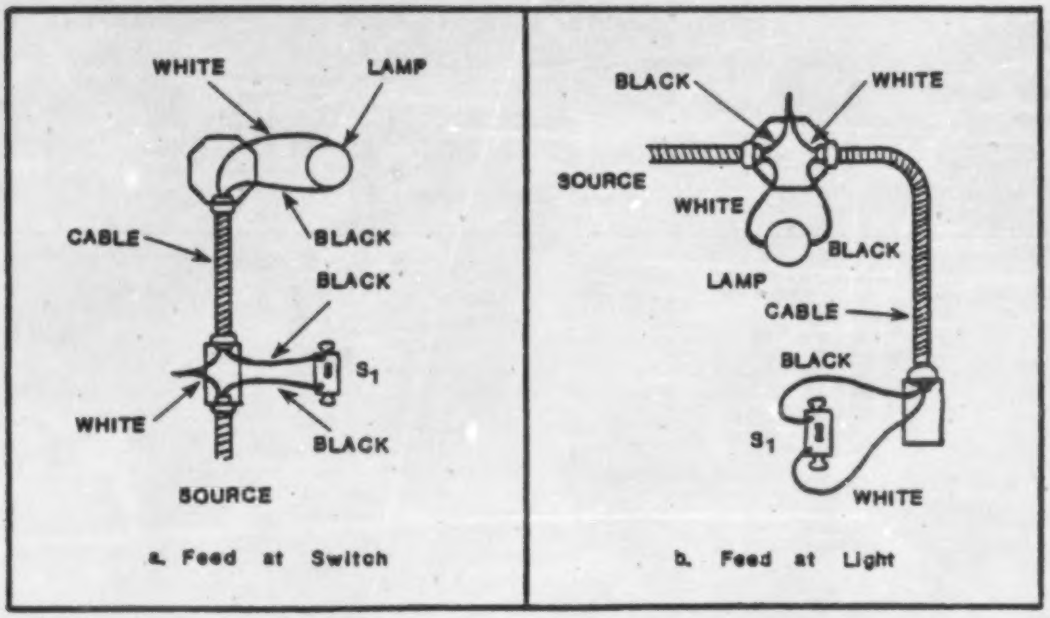

WHITE
LAMP
CABLE
BLACK
BLACK
S1
WHITE
BLACK
SOURCE
a. Feed at Switch
BLACK
WHITE
SOURCE
WHITE
BLACK
LAMP
CABLE
BLACK
S1
WHITE
b. Feed at Light

Figure 12. Single-Pole Switch Connections.

This conforms with the rule that the ground wire must be white at each outlet and the hot wire must be another color. The cable used for the switch loop contains one white wire and one black wire, but neither of these wires is at ground potential. All wires to switches in residential circuits are hot wires, regardless of color. This arrangement allows the use of standard cables in switch loops.

Figure 13 shows a circuit connection with three-way switch control. The source is at the first switch. In this case, the continuous white conductor extends to the lamp outlet; the switch loop is comprised of the black and red conductors.

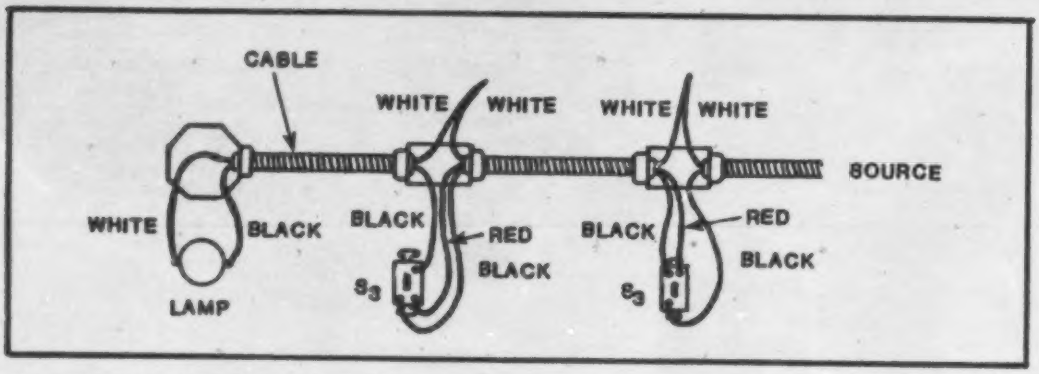

CABLE
WHITE
WHITE
WHITE
WHITE
SOURCE
WHITE
BLACK
BLACK
RED
BLACK
BLACK
RED
BLACK
S3
S3
LAMP

Figure 13. Circuit with Three-Way Switch Control, Feed at the First Switch Control Point.

Figure 14 is a similar circuit with the source at the lamp. At the lamp outlet, the white wire is the ground wire and the black wire is the hot conductor from the switch loop.

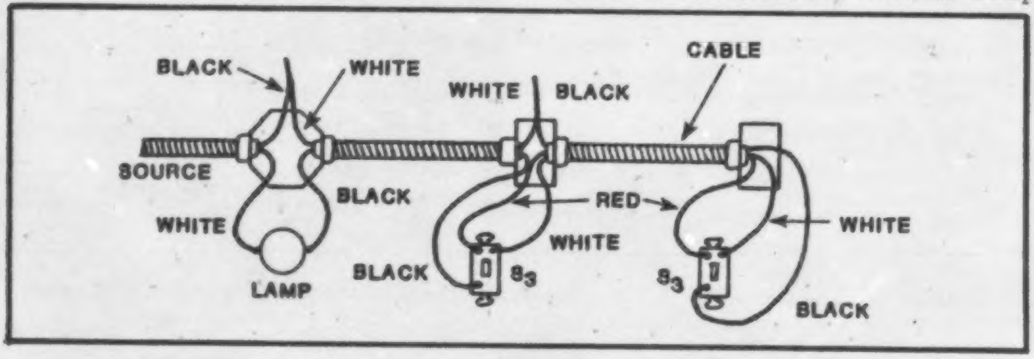

BLACK
WHITE
WHITE
BLACK
CABLE
SOURCE
BLACK
RED
WHITE
WHITE
WHITE
BLACK
S3
S3
LAMP
BLACK

Figure 14. Circuit with Three-way Switch Control, Feed at Light.

As in Figure 12b, the white wire is used as a hot wire in the switch loop. The circuit is connected in such a way that the outlet is served by a white ground wire and a hot wire of another color (usually black).

The only situation in which white wire may be used for any purpose other than a ground wire is in switch loops.

SUMMARY

The National Electric Code specifies the methods of installing electrical equipment to ensure that the finished job is safe. Underwriters Laboratory tests equipment and lists equipment that passes minimum safety standards. Local codes are usually based on the NEC and will certify for use only the equipment listed by UL.

Important safety features of all residential electrical systems include the following:

- The main service entrance and each branch circuit are protected by either fuses or circuit breakers in the hot line.
- All switches and protective devices are installed in the hot wires.
- The ground wire is white and contains no circuit devices.
- Each outlet is served by a white ground wire and a hot wire of another color (usually black).
- Each size and type of wire is used only for applications for which it is approved by the NEC.
- All circuit devices must be contained in approved boxes.
- A grounding system composed of bare wire, insulated wire that is green or green with a yellow stripe, or continuously connected conduit, is used to ground all circuit devices.
- All splices and connections must be made in an approved manner to assure safe operation of the system.

EXERCISES

1. Draw circuit diagrams of the following switches in residential circuits:
    a. Single-pole
    b. Double-pole
    c. Three-way
    d. Four-way
2. Describe the application of double-pole switches in residential circuits.
3. Sketch a diagram of a duplex outlet. Identify the colors of the terminals and specify the colors of wire that may be connected to each terminal.
4. Describe each of the following fuse types and their applications:
    a. Edison-base
    b. Type S
    c. Type SC
5. Describe the characteristics and uses of the following wires and cables:
    a. T
    b. THWN
    c. 12-2G type NMC
    d. 10-2G type UF
    e. 14-3 type AC
6. Explain how voltage drop affects the efficiency of residential circuits and the devices used on those circuits.
7. List the conditions under which the ampacity of a conductor must be de-rated.
8. Explain the difference in a grounded conductor and a grounding conductor in a residential circuit.

9. Describe three types of conduit that may be used in residential circuits.
10. Describe the characteristics of acceptable splices in conductors. Include the purpose of solder and the insulation requirements of splices.
11. Draw circuit diagrams of the following circuits. Include the grounding conductors:
    a. Single-pole switch controlling an outlet with the source at the switch.
    b. Two three-way switches controlling an outlet with the source at the outlet.
    c. Two three-way switches and a four-way switch controlling an outlet with the source at the first switch. Assume that four-conductor cable is used to connect the four-way switch and include an acceptable conductor arrangement.

LABORATORY MATERIALS

Grounded power cord (14-3)
Three boxes for mounting one switch or duplex outlet each
Two three-way switches
One duplex outlet
Five cable clamps for boxes
Five feet of 14-2G type NM or NMC cable
Five feet of 14-3G type NM or NMC cable
Wire nuts for connecting two number 14 conductors
Screwdriver
Wire cutters and strippers
Desk lamp, radio, or other low current device to be operated on the constructed circuit

LABORATORY PROCEDURES

1. Construct the circuit shown in Figure 14 using the materials provided and following the procedures outlined in the Subject Matter. The source for this circuit is the grounded power cord. Install the end of the cord without the connector in the lamp as if it were a standard cable.
2. Connect the green conductor of the cord to the bare ground conductor of the cable and securely ground each circuit device in an acceptable manner.
3. Check all terminal connections to be sure they are made in an acceptable manner and that the correct wires are installed on the proper terminals.
4. Follow the ground (white) conductor through the circuit to the outlet. Be sure the ground conductor is unbroken and contains no circuit devices.
5. The instructor should check the student's circuit before the power cord is plugged in.
6. After the instructor approves the circuit, plug the power cord into a 120-V outlet and plug the device to be operated into the duplex outlet. Operate the circuit and check for proper operation.
7. Draw a detailed circuit diagram in the Data Table. Include the connections of the grounding wire and the power cord.
8. Describe the operation of the circuit and each circuit component in the Data Table.

DATA TABLES

DATA TABLE.

CIRCUIT DIAGRAM:

DESCRIPTION OF CIRCUIT:

REFERENCES

Mullin, Ray C. Electrical Wiring – Residential. Albany, NY: Delmar Publishers, 1978.

Richter, H.P. and Schwan, W.C. Practical Electrical Wiring. New York: McGraw-Hill Book Company, 1978.

National Electric Code, 1978 Edition. National Fire Protection Association, 470 Atlantic Ave., Boston, MA 02210, 1978.

TEST

Please circle the appropriate answer.

1. The National Electric Code is ...
   - a. concerned with the safety and efficiency of the completed installation.
   - b. concerned with the approval and testing of individual components and the safety of the finished installation.
   - c. the established law governing all electrical installations.
   - d. concerned only with the safety of the finished job.
   - e. Both c and d are correct.
2. Which of the following is not acceptable as the grounded conductor of a residential electrical system?
   - a. A gray wire
   - b. A black wire, number 4 or larger, with the ends painted white
   - c. A white wire
   - d. None of the above are acceptable.
   - e. All of the above are acceptable.
3. A green wire in a cable may be used ...
   - a. for any purpose, if the system is not grounded.
   - b. as the circuit ground conductor.
   - c. for equipment grounding only.
   - d. as a hot wire only.
   - e. for none of the above purposes.
4. Double-pole switches are used in residential circuits ...
   - a. when it is desirable to disconnect the grounded conductor as well as the hot conductor.
   - b. to control an outlet from two locations.

c. only in 240-V circuits in which neither of the current-carrying conductors is grounded.
d. for most common applications.
e. None of the above are correct.

5. A cable designated 12-2G type NMC ...
   a. actually contains three conductors.
   b. cannot be used in wet locations or buried in the ground.
   c. is acceptable for damp locations.
   d. All of the above are correct.
   e. Only a and c are correct.
6. Which of the following is not an acceptable connection of a wire to the terminal of an outlet?
   a. A bare wire connected to a green screw
   b. A black wire connected to a brass screw
   c. A gray wire connected to a silver screw
   d. A red wire connected to a brass screw
   e. A white wire connected to a brass screw
7. Wires often carry a lower current than their nominal rated current when ...
   a. two current-carrying conductors are contained in a single conduit or cable.
   b. branch circuits have runs of over 100 feet.
   c. wires are subject to a continuous load of more than three hours duration.
   d. All of the above are correct.
   e. Only b and c are true.
8. When switch loops are composed of cables ...
   a. the white wire leading to the switch may be a grounded wire, but this is not required.
   b. the white wire leading to the outlet may be a grounded wire, but this is not required.

c. the white wire leading to the switch is always a hot wire.
d. the hot wire leading to the outlet may be white.
e. Both c and d are true.

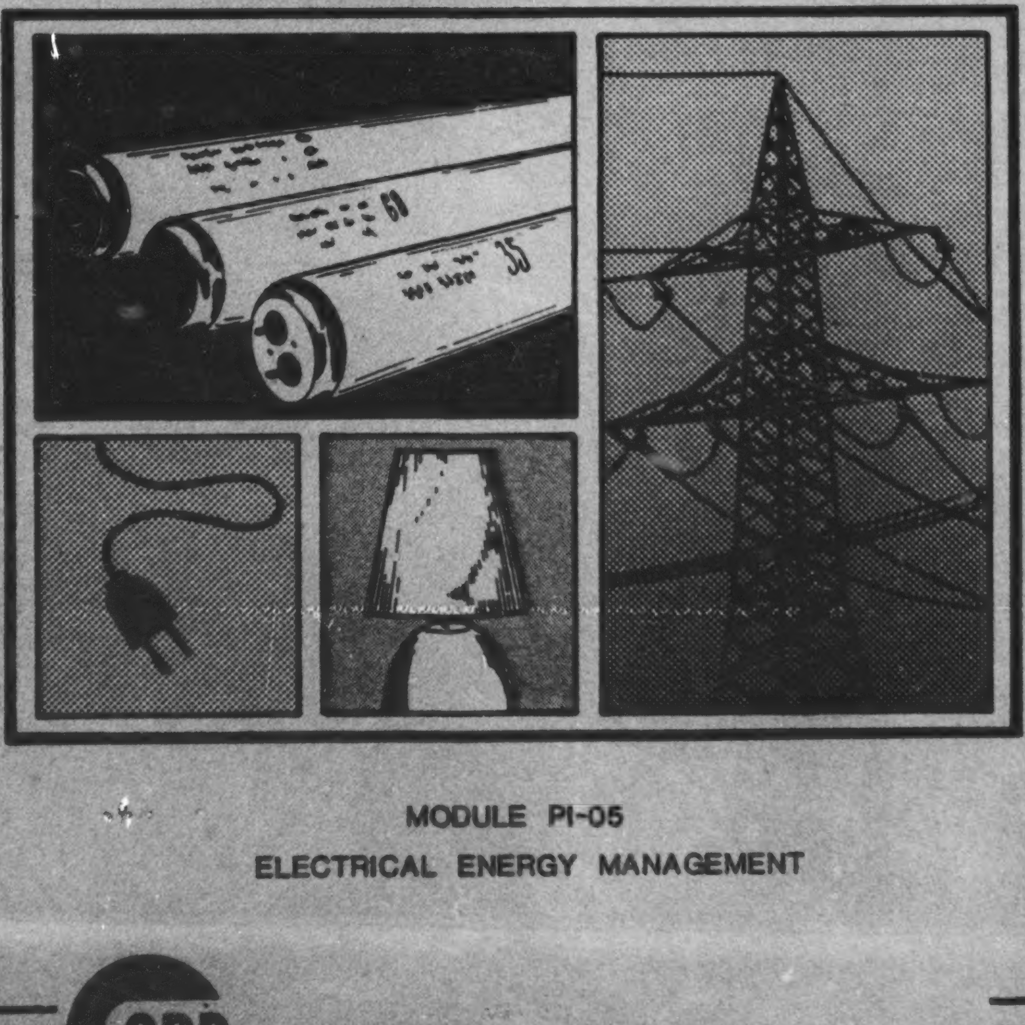
9. Splices in wires and cables ...
a. are not allowed in residential circuits.
b. may be made only inside boxes or straight conduit runs.
c. are usually soldered to assure good electrical contacts.
d. may be made with wire nuts only.
e. None of the above are correct.

10. Voltage drops in residential circuits ...
a. are usually of no concern, since voltage drops rarely exceed 1%.
b. produce losses in the lines, but do not adversely affect the operation of equipment.
c. should always be calculated and reduced to not more than 5% in any branch circuit.
d. are usually held to not more than 2% in any branch circuit.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-05

ELECTRICAL ENERGY MANAGEMENT

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

For many years, cheap, abundant energy fostered wasteful energy practices. In recent years, increased demands and dwindling supplies have driven energy prices up and made conservation essential for both residential and industrial consumers. This module describes methods of electrical energy management. Industrial and commercial customers can use electrical energy management techniques to reduce their expenditures for energy.

PI-05, "Electrical Energy Management," begins with a description of the costs involved in producing and distributing electrical energy and an explanantion of how these costs vary with fluctuating demands for power. Electricity production and distribution costs are the basis of the utility rate schedules described later in the module. Other topics include energy conservation in industry, power factor correction, descriptions of industrial loads, and the use of load management techniques to reduce the maximum power demand. The most common method used to calculate industrial electric bills is also explained.

In the laboratory, the student will calculate a series of electric bills and explore the effect of energy conservation and load management on utility costs.

PREREQUISITES

The student should have completed Module PI-04, "Residential Electrical Distribution."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and explain a diagram showing the variations in demand for electrical energy during a 24-hour period.
2. Explain the inefficiencies in electrical power production during minimum demand periods and peak demand periods.
3. Explain the basic characteristics and efficiencies of the following classes of industrial electrical loads:
   - a. Lighting
   - b. Heating
   - c. Motors
4. Explain how each of the following may be used to reduce electrical energy consumption:
   - a. Energy awareness
   - b. Maintenance programs
   - c. Power factor correction
   - d. Alternate energy sources
5. Explain the following terms as they are applied to industrial electrical loads:
   - a. Diversity
   - b. Diversity factor
   - c. Demand
   - d. Demand factor
   - e. Connected load
   - f. Load factor
   - g. Hours use of demand
   - h. Coincidence factor
   - i. Demand interval
6. Explain the purpose of electrical load management.

7. Calculate the monthly electric bill for an industrial installation, given the utility rate schedule and the following data for the month:
   a. Energy consumed
   b. Demand
   c. Power factor
8. Explain the term "load shedding" and describe loads that are – and are not – considered for load shedding.
9. Describe the following methods of load management:
   a. Timed method
   b. Manual method
   c. Ideal rate method
   d. Instantaneous rate method
   e. True forecast method
10. Given data for an industrial electrical load before and after the implementation of an energy management program, determine the following:
    a. Savings due to power factor correction
    b. Savings due to conservation
    c. Savings due to load management
    d. Total savings

ECONOMICS OF ELECTRICAL POWER PRODUCTION

Managing electrical power for industrial and commercial application to reduce both energy consumption and utility bills requires an understanding of factors that contribute to the cost of producing and distributing electrical energy. Industrial utility rates are based on several cost factors. This section explains how those factors increase the cost of electrical energy production and how those costs are met.

VARIATIONS IN DEMAND

Figure 1 shows the typical variation in demand for electrical energy during a day. The shape of this curve changes somewhat with the geographic region, season of the year, and predominant load type. However, the general shape will usually be similar to the shape in Figure 1.

The lowest loads usually occur during early morning hours when most people are asleep. During pre-dawn hours, some industries and commercial operations are using power, and some indoor and outdoor lighting is required. Demand typically begins to rise around 6 a.m. as people get up and more commercial and industrial users require power. Power requirements rise to a maximum early in the working day and remain high until lunch time.

At noon, there is a dip in demand as many commercial and smaller industrial consumers reduce consumption during lunch. After lunch, demand rises again and usually reaches its daily

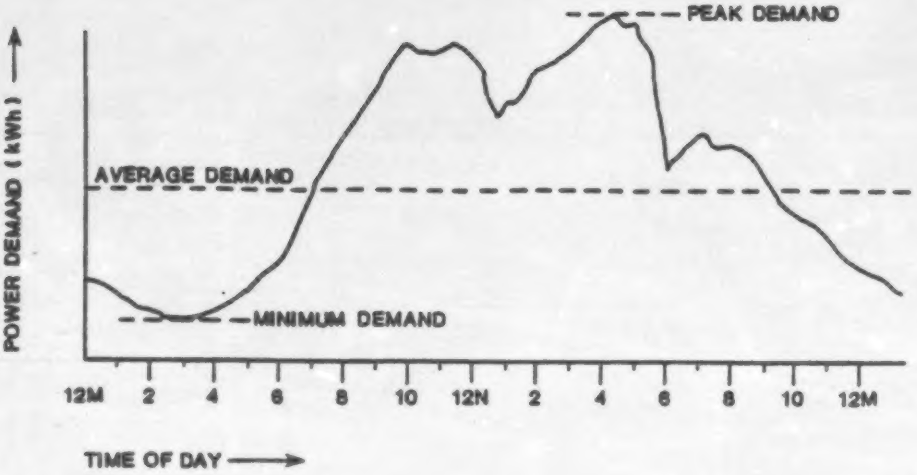


Figure 1. Typical Electrical Utility Daily Demand Cycle.

peak during the afternoon. At 5 p.m. there is a sharp drop when many businesses close for the day and employees head for home.

Demand rises again between 6 and 8 p.m. as residential use increases. Many commercial and industrial demands continue. Outdoor lighting is turned on. After about 9 p.m., demand drops steadily until the early morning minimum is reached.

There are also weekly, monthly, and yearly demand cycles, and the shape of the daily cycle may change considerably during the year. In colder climates, demand is higher in winter and the peak load may occur early in the working day when the need for heat is greatest. In hot climates, demand is highest in the summer when air conditioning loads are high. Peak daily demands occur in late afternoon. High demands may continue well into the night.

Figure 1 also shows the minimum demand, the peak demand, and the average demand. Since electrical power is generated at the same rate at which it is consumed, the utility company must coordinate power production with demand. The overall power system must be capable of meeting peak demands and have extra capability as a safety margin. Production must also be reduced to coordinate with diminishing requirements during minimum demand periods.

COST OF MEETING PEAK DEMANDS

Electrical power system generating and transmission capabilities must be capable of producing the necessary peak power and distributing it efficiently to customers. Transmission lines, transformers, and control equipment must be sized according to peak demand. During peak demand periods, many generating plants in the system will be in operation.

Older, less efficient facilities that are not used at other times are brought into service when demand rises. Gas turbines are often used to boost production during peak loads because they can be brought into operation quickly. Gas turbines are not used at other times because they are inefficient and gas is usually the most costly fuel. Thus, peak demands increase the overall cost of electrical power. This is because more expensive equipment is needed to transmit the peak power and this additional power is produced by less efficient means.

INEFFICIENCIES OF MINIMUM DEMANDS

Electrical energy production also costs more per kilowatt-hour during minimum demand periods. Only the largest and most efficient generating plants are in operation, but these plants are operating at reduced capacity and, thus, lower efficiency. Transmission line losses are reduced because of lower currents, but this is offset by other factors. Transformers operate most efficiently at — or near — their rated load. At reduced load, transformer efficiencies drop. All energy-consuming control devices must continue to operate, and personnel are still required for system operation. The periods must be paid for by the utility company through the sale of power. During minimum demand periods, much of this equipment is idle or operating far below its capacity, thereby not producing a profit or even paying for itself.

INEFFICIENCIES OF POOR POWER FACTORS

The power factor of an a.c. circuit was discussed in Module PI-01, "Efficiencies of Electrical Distribution Systems." Recall that at a power factor of 1.0, the system is most efficient. Lower power factors result in higher currents for the same useful power. This increases both line losses and voltage drop on the lines. Lower power factors also reduce the efficiencies of transformers and generators. Utilities increase the power factor through the use of capacitors and synchronous reactors and, thus, increase system efficiency.

WHO PAYS THE PRICE?

The customer always pays — not only for the power consumed but also for system inefficiencies — either through higher rates or special charges. The cost of equipment to meet peak demands is recovered by demand charges to larger consumers. The electrical energy costs of larger consumers depend on energy used and the maximum rate of use. Discount rates are often available on energy used during low demand periods to encourage a more even distribution of the demand. The power factor is always corrected in the transmission and distribution system. If the customer corrects the power factor, the utility has to do less correction and charges a lower rate.

In one way or another, the customer always pays for peak capabilities and inefficiencies, and the price is always less if both peak demand and energy waste can be reduced by the customer. Thus, an effective electrical energy management program has two major objectives: (1) to reduce total energy consumption, and (2) to distribute the load as evenly as possible.

INDUSTRIAL ELECTRICAL LOADS

Industrial electrical loads are usually classified as lighting loads and power loads. Power loads may be subdivided into heating loads and motor loads. This section briefly discusses each load type.

LIGHTING LOADS

About 20% of the electrical power produced in the U.S. is consumed by lighting loads. Lighting loads are usually the least efficient type. For example, incandescent lamps convert between 7.5% and 15% of the energy they consume to useful light, with larger-wattage lamps having the highest efficiencies. Fluorescent lights have an efficiency of slightly over 20%. High-intensity discharge lamps have efficiencies in the range of 50% and 70%. Therefore, most of the light that is produced is wasted.

Many areas have illumination levels that are higher than necessary and much of the light is directed to places where it is not needed or is absorbed by surfaces. Significant energy savings can often be achieved by more efficient lighting systems. The power factor of incandescent lights is 1.0. Other types have a lagging power factor because of the inductance of the lamp ballasts. The last three modules of this course discuss lighting systems in detail.

HEATING LOADS

Electrical power is commonly used to heat buildings, water, and materials in industrial processes. Electric heating is seldom the primary heat source for large buildings, but electric duct heaters and reheat units may be used to supplement other more economical types of heat. Smaller structures may depend entirely on electricity for heating needs.

Water may be heated – either for use as hot water or steam – by two types of heaters. Emersion heating elements convert electrical energy to thermal energy in metal conductors that are immersed in water. Electrode heating elements pass a current directly through the water to produce a heating effect.

Ovens are heating devices that operate at temperatures of 1,000°F or lower. They employ resistive elements similar to those used for space heating. The efficiency of all electrical resistive heaters is close to 100%, and the power factor is 1.0.

Furnaces are heating devices that operate at temperatures above 1,000°F. When the material to be heated is a nonconductor of electricity, resistive heating elements may be used. Capacitance, or dielectric heating, is accomplished by placing the nonconductor between the plates of a large capacitor and applying a high-frequency electric field. This causes distortions in the molecular structure of the material and produces heat.

Conductors are usually heated by passing a current through the material itself. This may be done as simple resistive heating of the material due to current flow, or by using electrodes above the material to produce arcs for heating. In induction furnaces, a coil of wire around the furnace (or in a core within the furnace) produces a strong alternating magnetic field in the conductor to be heated. This induces currents that do the heating. All furnaces with resistive heating have power factors of 1.0 and efficiencies of close to 100%. Capacitive and inductive heaters have lower efficiencies and power factors.

MOTOR LOADS

Industry's chief power requirement is usually for the power necessary to operate electric motors. For instance, the power consumed by air conditioning systems is used to operate motors that drive compressors, pumps, and fans. In addition, all industrial facilities require motors for production processes.

Induction motors are the most common motor type and are available in a wide range of sizes and speeds from about 450 rpm to 3,600 rpm. Induction motors up to about 700 hp can operate at one or more speeds within this range. Larger induction motors – up to 10,000 hp – usually operate at 1,800 rpm or 3,600 rpm. The efficiency of induction motors varies from 88% for smaller models to 95% for large models. Maximum efficiency occurs at, or near, full load. There is usually little drop in efficiency at 85% of full load, but below that figure, induction motor efficiency drops considerably. The power factor of induction motors is about 0.9.

Synchronous motors are available in the same general power and speed ranges as induction motors, although few operate at more than 1,800 rpm. Synchronous motors may have speeds of 360 rpm or less. Synchronous motors are used for most applications where the power is above 700 hp and the speed is 1,200 rpm or lower. The power factor of synchronous motors may be adjusted for either leading or lagging power. Most synchronous motors are operated with a power factor of 1.0, but if installed with induction motors, synchronous motors can be operated with a leading power that offsets the lagging power factor of induction motors. Synchronous motor efficiencies are slightly higher than those of induction motors of the same power rating.

REDUCTION OF ENERGY WASTE

Obviously, the best way to lower energy costs and conserve energy is to use less energy. An abundant supply of low-cost energy has contributed to energy waste. However, as energy becomes less abundant and more expensive, conservation efforts become important as an economic necessity. Several energy conservation techniques are discussed in this section.

ENERGY AWARENESS

The first rule for electrical energy conservation is: If the electrical device is not needed, turn it OFF. Most electrical energy waste occurs when electrical devices continue to operate when they are not being used. Much of this waste can be eliminated by energy conservation awareness programs. Energy conservation can be particularly effective in reducing lighting loads. Lighting levels should be reduced when high levels are not required and when natural light supplies some, or all, of the necessary light.

EQUIPMENT AND FACILITY MODIFICATION

Significant long-range savings can often be achieved by replacing older equipment with new energy-efficient equipment, even though the old equipment is still functioning.

Electrical distribution systems with a total full-load voltage drop of 5% should be upgraded.

Motors operating at well below their rated power should be replaced with smaller motors.

Incandescent lighting should be eliminated, and high-intensity discharge lights should be used whenever possible.

Increasing building insulation, installing heat – reflecting glass, and employing heat recovery systems can reduce heating and cooling requirements.

MAINTENANCE PROGRAMS

Poorly-maintained equipment is less efficient than well-maintained equipment, and maintenance programs that take energy efficiency into account can save both energy and money. The useful life of mechanical equipment can also be extended by better maintenance practices.

POWER FACTOR CORRECTION

Since most loads have lagging power factors, power factor correction must be applied somewhere in every power distribution system. If the utility company does the correcting in the distribution system, the utility company charges the customer a fee. Moreover, the poor power factor and resulting inefficiencies are still present at the customer's facility. It is to the customer's advantage to correct the power factor at the point of origin. Although it is usually economical to correct the power factor to 0.95, correction to 1.0 is seldom justified.

Figure 2 shows several possible locations for capacitors to correct the power factor. Capacitors for large motors

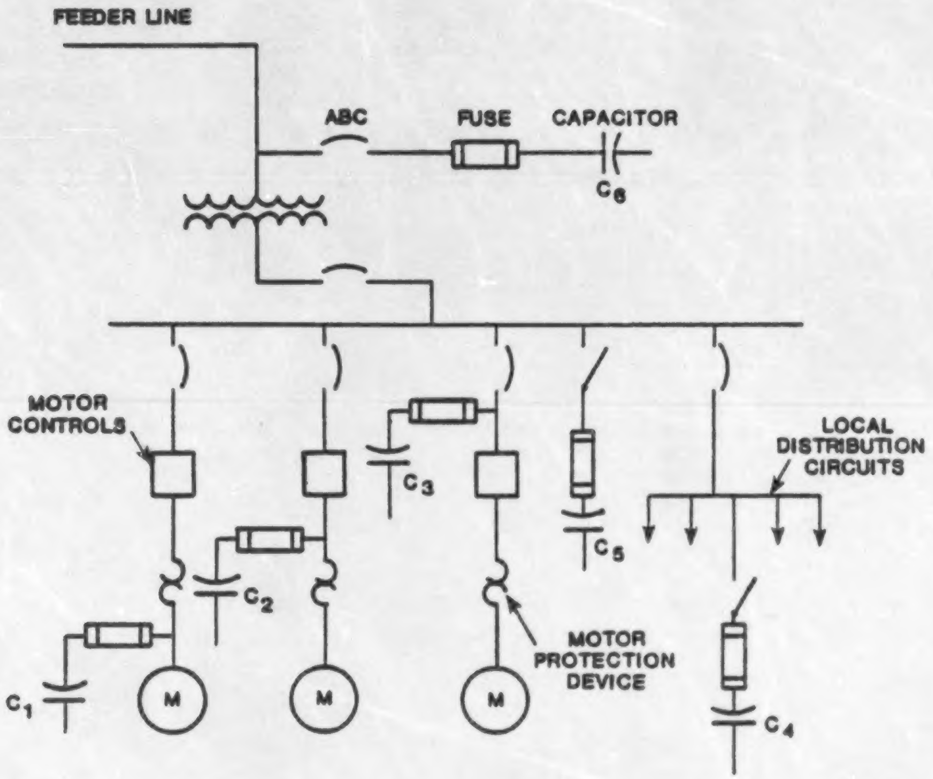

FEEDER LINE
ABC
FUSE
CAPACITOR
C_6
MOTOR CONTROLS
LOCAL DISTRIBUTION CIRCUITS
C_3
C_5
C_2
MOTOR PROTECTION DEVICE
C_1
M
M
M
C_4

Figure 2. Capacitor Locations for Power Factor Correction.

should be located near the motor and should be connected to the circuit only when the motor is in operation. It is preferable to connect the capacitor directly to the motor (C_1).

If this interferes with motor protection devices, the capacitor can be connected at the motor controls (C_2).

Both arrangements allow the capacitor to be switched by the motor controller. The capacitor can also be connected at the breaker panel (C_3) and controlled by the circuit breaker that controls the motor. Any other arrangement requires separate control switches for capacitors.

In systems with a large number of smaller loads, capacitors may be connected at load centers (C_4) on the primary feeder lines (C_5). The least efficient method is to include the capacitors in the substation (C_6).

ALTERNATE ENERGY SOURCES

In many cases, alternate energy sources may be used to reduce both electrical energy consumption and peak demand. This is most frequently accomplished by alternate heat sources. The waste heat from lights and industrial processes may be used to provide part of the heating requirements. Solar collectors and fossil fuel heating facilities may also be economical. The energy requirements of HVAC systems may be reduced by installing heat exchangers between the exhaust and ventilation ducts.

ELECTRICAL LOAD CHARACTERISTICS

Both electrical energy rates and electrical energy management techniques depend upon load characteristics. This section describes important characteristics of electrical loads and the terms used in those descriptions.

DIVERSITY

The connected load is the sum of the full load continuous ratings of all electrical devices in a composite load system. Rarely does the entire load operate at the same time. A system with a varying load is said to be diversified.

Figure 3 shows a composite load made up three individual loads. Load 1 is continuous and is not diversified at all. Load 2 has considerable variations and is diversified. Load 3 has even larger variations and is more diversified. The composite load is also highly diversified. The average load for this time period is also shown. Load management is applied to diversified loads to reduce the peak load and bring the instantaneous composite load nearer the average load at all times. Effective load management requires diversified individual loads and results in a composite load of low diversity.

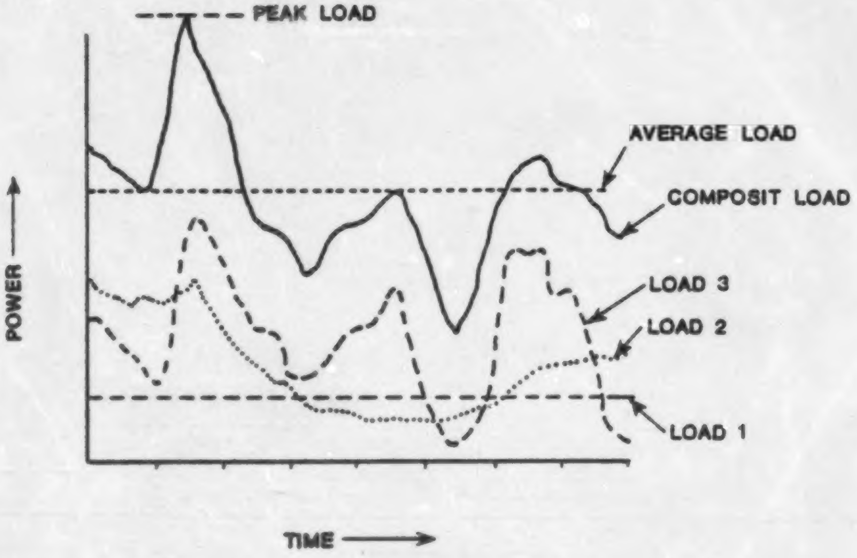


Figure 3. Composite Load with Diversity Factor of 1.0.

The diversity factor of a composite load is the ratio of the sums of the maximum demands of the individual loads to the maximum demand of the system. If the maximum demands of the individual loads occur at the same time as shown in Figure 3, the diversity factor is 1.0. This results in the highest possible peak demand for the system and the highest demand charge on the electric bill.

Figure 4 shows the same individual loads except that load 3 is delayed slightly. This increases the diversity factor to greater than 1.0 (about 1.2 in the figure) and lowers the peak demand of the system. A further reduction of peak demand could be achieved at the same average demand if the diversity of load 3 could be reduced by lowering its individual demand at time T_1 and by increasing its individual demand at time T_2.

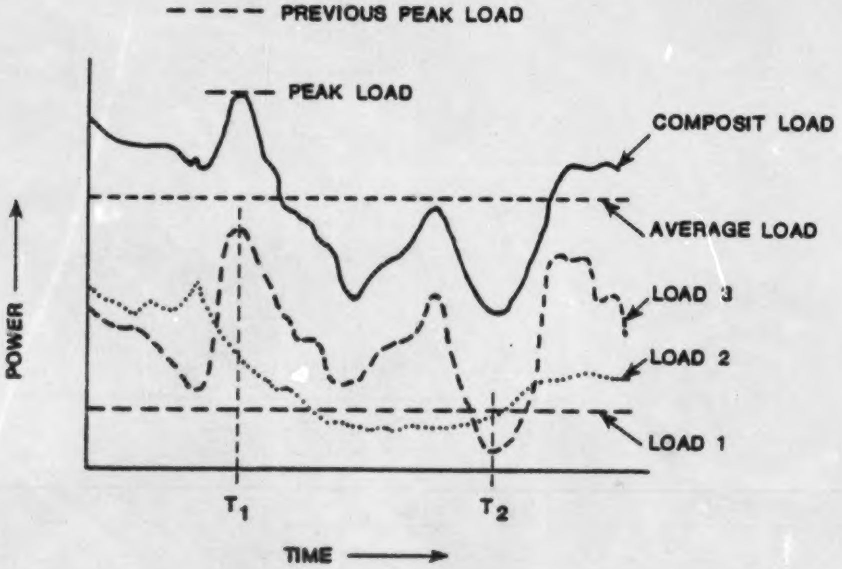


Figure 4. Composite Load from Figure 3, with Diversity Factor Increased by Delaying Load 3.

DEMAND

The demand is the average load imposed on the electrical supply system over a period of time called the demand interval.

If Figures 3 and 4 represented one demand interval, the demand would be the power level indicated by the average load line. The demand interval is defined by the utility company and is usually 15, 30, or 60 minutes.

Demand charges are based not on the instantaneous peak demand, but on the highest average demand achieved in any demand interval during the billing periods. A billing period of 30 days or 720 hours, with a demand interval of 15 minutes, contains 2,880 demand intervals. The demand charge is determined by the demand of the interval during the month having the highest demand (average for 15 minutes).

During a billing cycle, the demand factor of a system is defined as the ratio of the maximum demand to the connected load. It denotes the maximum percentage of the connected load that is operated at any one time during the billing cycle. Reducing the demand factor for an installation also reduces the demand charges.

The coincidence factor is the ratio of the maximum demand of the composite load system to the sum of the maximum demands of the individual or composite loads. It is the inverse of the diversity factor and, thus, is always 1.0 or less.

LOAD FACTOR

The load factor is the ratio of the average load for a particular time interval to the peak load that is achieved during that interval.

For billing purposes, the time interval is usually the billing period. The peak load is the maximum demand during any demand interval. The load factor indicates the extent to which the system capability was used during the billing period. Load factor is the ratio of the energy actually used during a time interval to the energy that would have been used if the load had been operated continuously during that interval at the peak demand. Higher load factors indicate greater use of system capabilities. A constant, continuous load has a load factor of 1.0.

The phrase "hours use of demand" may also be used to express the load factor of a system. Hours use of demand is determined by dividing the kilowatt-hours accumulated during a time interval by the maximum demand during that interval in kilowatts. The result is expressed in hours and is the time that would have been required to use the total energy consumed during the interval if it had been used continuously at the maximum rate. For a constant, continuous load, the hours of demand for an interval equals the duration of that interval in hours.

POWER FACTOR

The power factor of a system is the ratio of the power consumed by the system in watts to the product of volts and amps of the system. A complete discussion of power factor is found in Module PI-01, "Efficiency of Electrical Distribution Systems."

UTILITY RATE SCHEDULES

In planning an electrical load management program, it is necessary to know the rate schedules of the local utility company. This section discusses typical rate schedules. Rates used as examples are 1977 rates of a typical Midwestern utility.

DEMAND CHARGE

Demand charges are usually based on the maximum demand during the billing period. Some utilities employ a ratchet rate to demand charges. In this system, the demand charge is based on the maximum demand in a period greater than the billing period. The charge may be based on the maximum demand during the last twelve-month period.

Typical demand charge:

First 25 kW of demand	$2.15 per kW per month
Next 475 kW of demand	$1.90 per kW per month
Next 1,500 kW of demand	$1.75 per kW per month
Excess over 2,000 kW of demand	$1.47 per kW per month

ENERGY CHARGE

The energy charge is based on the total energy consumed per month. Rates are currently set so that larger customers pay less per kilowatt-hour. This practice tends to discourage conservation efforts and may be altered in the future to reduce savings to larger customers and, thus, encourage greater conservation efforts.

Typical energy charge:

First 2,000 kWh per month	$0.02 per kWh
Next 18,000 kWh per month	$0.015 per kWh
Next 180,000 kWh per month	$0.011 per kWh
Next 550,000 kWh per month	$0.009 per kWh
Next 250,000 kWh per month	$0.0085 per kWh
Excess over 1,000,000 kWh per month	$0.0082 per kWh

LOAD FACTOR DISCOUNT

Charges for poor load factor may take several forms. Customers who maintain a certain load factor are usually given a discount. This discount is often expressed in terms of the hours use of demand. Typically, this discount applies only to customers who have a load factor greater than 0.5; that is, an hours use of demand in excess of 360 hours for a 720-hour billing period. Only larger customers can achieve this criterion. A constant load would have to be operated for 12 hours per day for the entire month before the discount would be applied. Qualifying customers usually operate for 24 hours per day and employ a good energy management program.

A typical load factor discount policy is:

A discount of $ $0.0015 per kWh is allowed on that portion of a customer's monthly consumption in excess of 360 hours use of his billing demand for the month.

POWER FACTOR PROVISIONS

Rate schedules always include penalties for poor power factor for larger customers. These rates are based on average power factor for the month and may take several forms. The most common rate schedule bases energy charges on a power factor of 0.8 and provides discounts for higher power factors and makes additional charges for lower power factors.

The following is a typical power provision:

> In the case of customers with maximum demands of 150 kW or more, the monthly rate shall be decreased 0.2% for each whole one percent by which the monthly average power factor exceeds 80% lagging, and shall be increased 0.3% for each whole one percent by which the monthly average power factor is less than 80% lagging.

FUEL CLAUSE

Fuel clauses allow utility companies to adjust rates according to the fluctuating costs of the fuels they use to produce electrical power. Essentially, this means that the customer – not the utility – pays the cost when fuel prices go up or when more expensive fuels must be used. Fuel clauses are not normally used when most, or all, of the power consumed in a system is generated by hydroelectric installations. Falling water is assumed to be free.

TIME-OF-DAY METERING

Some utilites offer discounts for power consumed during system minimum demand periods. This usually takes the form of a discount on demand charges. To qualify for such demands, a customer must operate so that the maximum demand occurs during the late night shift. This method is not practical for most customers, but results in considerable savings if it can be used. The method is practical, for example, for water companies that operate large pumps during late night hours to pump water into storage tanks for use the next day.

Example A illustrates how to calculate a monthly electric bill using the given rate schedule.

EXAMPLE A: CALCULATION OF ELECTRIC BILL.

Given: A large industrial plant had the following electrical service data for one month:

Maximum demand: 1,356 kW
Energy consumed: 640,320 kWh
Average power factor: 92%

Find: The electric bill for the month, based on the rates stated as examples in this module. Assume no fuel clause and no time-of-day discount.

Solution: Demand Charge ...

First	25 kW	(25) ($2.15) =	$ 53.75
Next	475 kW	(475) ($1.90) =	902.50
Next	856 kW	(856) ($1.75) =	1,498.00
Total	1,356 kW		$2,454.25.

Example A. Continued.

Energy Charge ...

First 2,000 kWh	(2,000) ($0.02)	=	$ 40.00
Next 18,000 kWh	(18,000) ($0.015)	=	270.00
Next 180,000 kWh	(180,000) ($0.011)	=	1,980.00
Next 440,320 kWh	(440,320) ($0.009)	=	3,962.88
Total 640,320 kWh			$6,552.88

Total bill = $9,007.13.

Load Factor Discount ...

$$\text{Hours use of demand} = \frac{\text{energy consumed}}{\text{maximum demand}}$$

$$= \frac{640{,}320\text{ kWh}}{1{,}356\text{ kW}}$$

$$\begin{array}{rl} \text{HUD} = & 472\text{ hours} \\ & -360\text{ hours} \\ \hline & 112\text{ hours of demand qualify for discount.} \end{array}$$

(112 h) (1,356 kW) = 151,872 kWh qualified for discount.

Discount = (151,872) ($0.0015)
= $227.81.

Power Factor Discount ...

92% - 80% = 12% qualified for discount

(12) (0.2%) = 2.4% discount from monthly rate

($9,007.13 (0.024) = $216.17 discount

Total discounts = $443.98.

Bill before discounts ...	$9,007.13
Discounts ...	-443.98
Net bill for month ...	$8,563.15.

ELECTRICAL LOAD MANAGEMENT

Load management is the process of scheduling the individual component loads of a composite load to reduce the demand and, thus, the demand charge. Load management does not greatly affect the amount of energy consumed; it evens out consumption, thereby reducing the inefficiencies of peak and minimum demand periods. This reduces the need for new generating facilities. In addition, the running time of less-efficient generating plants in the power system is also reduced. The customer realizes these savings in lower demand charges. Load management also reduces the demand on customer-owned electrical distribution equipment, resulting in more efficient operation and delaying the need for increasing in-plant distribution capabilities.

ELECTRICAL ENERGY AUDITS

The first step in a load management program is to conduct an electrical energy audit to determine the characteristics of the composite load. Power companies will provide data on the total load and will usually assist the customer in performing the audit.

It is necessary to monitor each of the individual loads in the system to assess the behavior of the components of the total load. The survey should last at least one full billing period (month) and should include data on night and weekend loads even if the facility is not in full operation at these times.

Energy audits should not be conducted once and forgotten. Load monitoring must continue to determine the effects of the load management program and to determine methods of making further improvements.

TIMED LOAD CONTROL

The simplest method of load control is to reschedule certain processes or to install timers that turn certain equipment items ON and OFF at set times.

This simple method often produces the most dramatic results. For example, a metal coating company in Hamburg, Pennsylvania, reduced its demand by 1,000 kilowatts for an annual saving of $40,000 on demand charges by rescheduling furnace loading from its first shift to the second. Timed load control can easily be applied to a wide range of industrial processes.

LOAD SHEDDING AND RESTORING

Load shedding is the process of monitoring electrical power consumption and turning OFF certain loads when the demand approaches a predetermined level. Loads that are shed are restored later when the total load has decreased. Some loads will consume the same total energy with load shedding. The energy that is saved at one time is consumed at a later time. These loads are called recoverable loads and include equipment such as air conditioners.

Non-recoverable loads are those that do not consume the energy that was saved and, thus, represent a saving on both demand charges and energy charges. An example of such a load is a ventilating fan that can be turned OFF or operated at a reduced power for certain periods of time.

Many loads are not eligible for load shedding. Many industrial processes must continue on a fixed schedule until completed to avoid ruining the batch or damaging the equipment. Large motors are not usually considered for load shedding because the major factor limiting motor life is the total number of motor starting operations. The following loads are often considered for load shedding/restoring operations:

- Arc furnaces
- Battery chargers
- Chillers
- Compressors
- Grinders
- Incinerators
- Pumps
- Water heaters
- HVAC equipment

Load shedding may be accomplished manually by the operators of certain major equipment items. Technicians must monitor the total demand and switch OFF high consumption equipment when the demand reaches a predetermined point. Manual load control is effective only in smaller operations, where the total load is composed of only a few component loads with one or more components that may be easily shed.

Larger facilities employ automated load control. Automatic load shedding is based on the demand interval established by the utility company. Its objective is to achieve a demand just under a predetermined target demand during each demand interval. Figure 5 shows the energy consumed versus time for one demand interval.

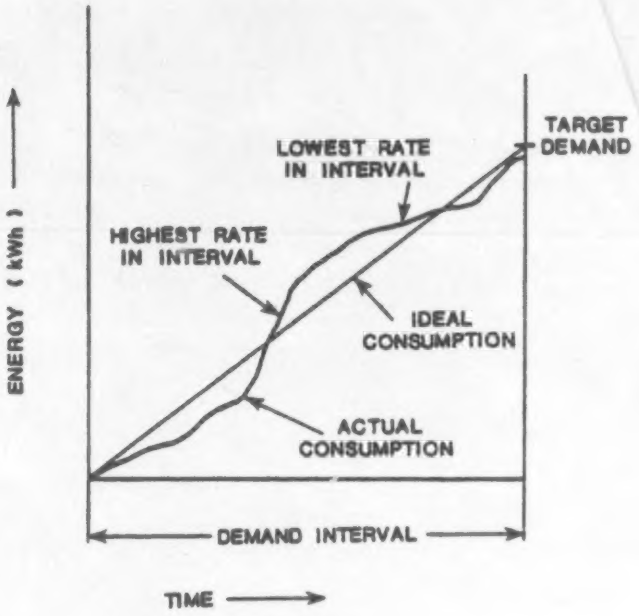


Figure 5. Ideal and Actual
Rates of Energy Consumption.

The rate of energy consumption is the slope of the consumption curve. A constant continuous load has a constant consumption rate and produces a straight-line, or ideal, consumption. Demand charges are based on the average demand during the demand interval. This is equivalent to the total energy consumed during the interval.

Variations in consumption rate during an interval do not affect the demand charge; only the total energy consumed during the interval is important. Loads are shed and restored during the interval in order to achieve the target demand. Loads are shed and restored in a priority sequence, with sufficient difference between shedding restoring criteria to prevent undesirable system oscillations.

IDEAL RATE METHOD

The ideal rate method of load control is illustrated in Figure 6. This method employs an ideal rate line that is generated within the controlling logic. This line is offset from zero at the beginning of the demand interval to prevent premature load shedding. The control logic compares the actual energy consumed at any time during the demand interval with the amount that would have been consumed if the load matched the ideal rate line. If the difference is small, loads are shed; if the difference is large, loads are restored. The logic receives an end-of-interval pulse from the utility metering equipment that tells it when to begin a new interval. All loads are usually restored at the beginning of each interval.

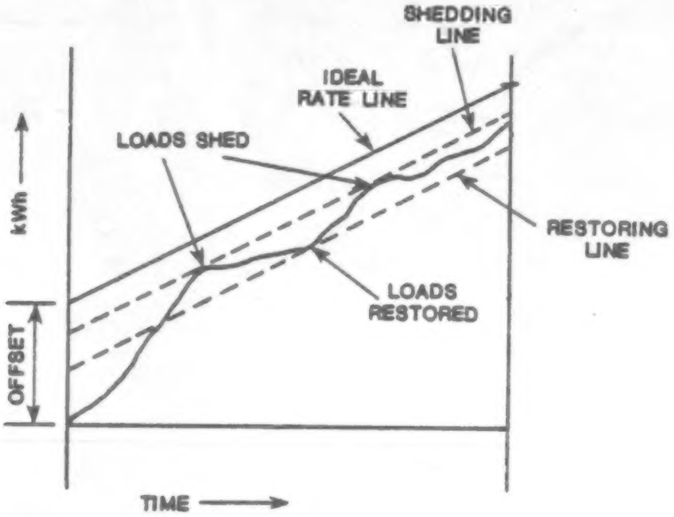

SHEDDING LINE
IDEAL RATE LINE
LOADS SHED
kWh
RESTORING LINE
LOADS RESTORED
OFFSET
TIME

Figure 6. Ideal Rate Method of Load Control.

INSTANTANEOUS RATE METHOD

Figure 7 illustrates the instantaneous rate method of load control. This method compares the instantaneous rate of energy consumption with an established ideal rate. If the instantaneous rate exceeds the ideal rate by a preset amount, loads are shed; if the ideal rate exceeds the instantaneous rate by a preset amount, loads are restored.

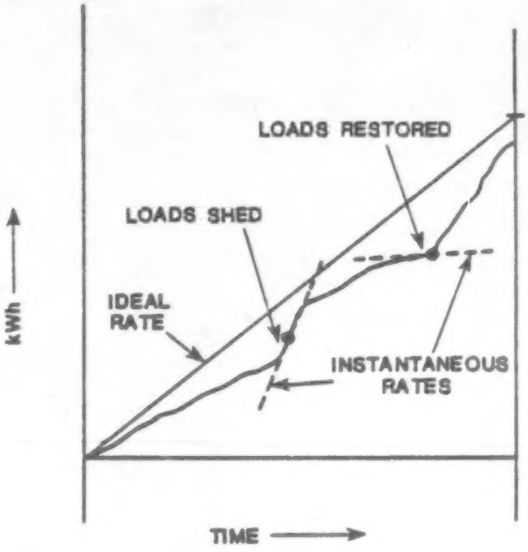


Figure 7. Instantaneous Rate Method of Load Control.

Shedding and restoring rates selected depend in part on the duration of the demand interval, but the logic of this system measures rates only and requires no end-of-interval pulse from the utility company equipment. Both the instantaneous rate method and the ideal rate method may be applied with fairly simple control equipment.

TRUE FORECAST METHOD

The true forecast method of load control (Figure 8) is the most efficient method and is accomplished by computer control in large load centers. The demand interval is partitioned into several smaller intervals. At the end of each interval, the computer calculates the accumulated energy to that point and determines the demand for the interval if the load is maintained at the same average rate. If the projected demand exceeds the target demand, loads are shed; if the projected demand is less than the target demand by a preset amount, loads are restored.

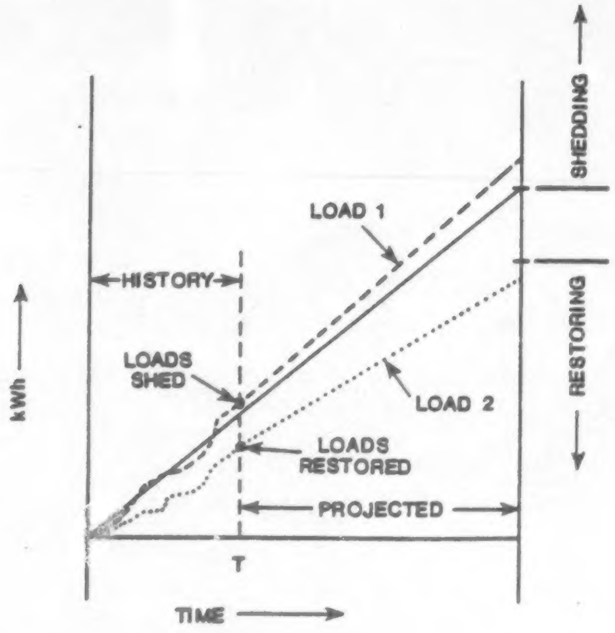

SHEDDING
LOAD 1
HISTORY
kWh
LOADS SHED
RESTORING
LOAD 2
LOADS RESTORED
PROJECTED
T
TIME

Figure 8. True Forecast Method of Load Control.

SUMMARY

Electrical energy production systems are most efficient if the energy delivery rate is near the average rate. During higher demand periods, less efficient equipment and more expensive energy sources are used to meet the higher demand. Distribution equipment must be sized for peak demands. At lowered demands, this equipment is less efficient. The costs of system inefficiencies are passed along to the customers in in the form of demand and fuel charges. Industrial electric utility rates are constructed to encourage the most efficient operation of the entire system.

Electrical energy management programs are designed to reduce energy costs by two major means. Conservation measures reduce the total energy consumed and, thus, the energy charges. Load management programs distribute the loads more evenly to reduce the peak demand and the ensuing demand charges.

EXERCISES

1. Draw and explain a diagram showing the variations in demand for electrical energy during a typical day.
2. Explain the costs of producing and distributing electrical energy, how these costs vary with fluctuating demand, and how these costs are reflected in industrial utility rates.
3. List three types of industrial electrical loads and describe the characteristics of each.
4. List and explain four methods that may be used to reduce energy consumption.
5. Define and explain the following terms:
   a. Diversity
   b. Diversity factor
   c. Demand
   d. Demand factor
   e. Connected load
   f. Load factor
   g. Hours of demand
   h. Coincidence factor
   i. Demand interval
6. Describe five methods of load management.
7. Explain the difference in load management and energy conservation.
8. Explain how alternate energy sources may be used to reduce both energy consumed and demand.
9. Explain load shedding and restoring and describe loads that may be shed and loads that cannot be shed.

Use the rate schedule given in this module to solve the following problems. Assume no fuel clause is used.

10. An industrial customer operates for 22 days in a month from 8 a.m. to 5 p.m. only. During the month, the energy consumption is 52,800 kWh; the maximum demand is 600 kW; and the power factor is 0.80. Determine the bill for the month.
11. The same customer is considering an energy management program. Determine the savings in dollars – and as a percentage of the above monthly bill – if the following measures are employed separately:
    a. Correction of power factor to 95%
    b. Reduction in energy consumed by 10%
    c. Reduction in demand by 30%
12. Calculate the new monthly bill and the percent savings if all three of the above are employed.
13. Based only on the information given in Problem 10, what is the most likely method for reducing demand?

LABORATORY MATERIALS

Pencil
Paper
Calculator

LABORATORY PROCEDURES

The laboratory for this module consists of a series of calculations of monthly electrical bills for industrial customers.

Demand factor, load factor, and hours of demand are also calculated. The laboratory instructor will provide the local utility rate schedule to be used in all calculations and load data on a local industrial customer.

1. List the local electrical utility rates in the Data Table.
2. Enter data on a local industrial customer in the Data Table in the column labeled "Customer C."
3. Determine the electric bill for the month for each customer.
4. Complete the Data Table.

OPTIONAL LABORATORY SUGGESTIONS

1. Use the current local utility rates to solve Problems 10, 11, and 12 of the Exercise section. Compare present energy costs with 1977 rates.
2. Contact the local electrical utility and request that a representative make a presentation describing the load rate schedule, methods used by the local utility to meet peak demands, and assistance the company provides to customers in the area of conservation and load management.
4. Contact local industries and arrange for a representative to discuss load management techniques that are being employed locally.

DATA TABLE.

LOCAL UTILITY RATE SCHEDULE

Demand Charge:

Energy Charge:

Load Factor Provision:

Power Factor Provision:

Fuel Clause (if available):

	Customer A	Customer B	Customer C
Connected Load			
Energy Consumed			
Maximum Demand			
Power Factor			
Demand Factor			
Load Factor			
Hours of Demand			
Demand Charge			
Energy Charge			
Load Factor Discount			
Power Factor Discount (or Penalty)			
Total Monthly Bill			

REFERENCES

Thumann, Albert. Plant Engineers and Managers Guide to Energy Conservation. New York: Van Nostrand Reinhold Co., 1977.

Vogt, Lawrence J. and Conner, David A. Electrical Energy Management. Lexington Books. Lexington, MA: D.C. Heath and Co., 1977.

TEST

Please circle the appropriate answer.

1. The purpose of electrical load management is to ...
   a. reduce energy consumption.
   b. reduce peak demands.
   c. improve power factor.
   d. Only a and b are correct.
   e. All of the above are correct.
2. Which of the following is the first load management technique to be considered for small installations?
   a. True forecast method
   b. Instantaneous rate method
   c. Ideal rate method
   d. Manual load shedding
   e. Process rescheduling and timed load control
3. Which of the following techniques is most effective for large load centers?
   a. Timed load control, combined with process rescheduling
   b. Ideal rate method
   c. True forecast method
   d. Instantaneous rate method
   e. Manual load shedding
4. Which of the following load management methods restores all the loads at the beginning of each demand interval?
   a. Manual load shedding
   b. Instantaneous rate method
   c. Instantaneous restoring method
   d. Timed load control
   e. Ideal rate method

5. Which of the following loads is least likely to be considered for load shedding?
   a. Water heater
   b. Arc furnace
   c. Battery chargers
   d. 250-hp electric motor
   e. Air conditioner compressor motor
6. Which of the following are true of demand charges?
   a. Demand charges are based on the greatest instantaneous demand during the demand interval.
   b. Demand charges are usually an insignificant portion of the total electric bill.
   c. Demand charges go down if the load factor goes up, with no change in energy consumed.
   d. All of the above are correct.
   e. Only a and b are correct.
7. Power factor correction of industrial systems ...
   a. reduces the demand charge.
   b. is economical to a correction of about 0.95, but not to 1.0.
   c. usually represents a greater overall savings than load management.
   d. All of the above are correct.
   e. Only b and c are true.
8. A non-recoverable load is one ...
   a. that cannot be considered for load shedding because of possible damage to equipment or materials being processed.
   b. such as a large electric motor, whose lifetime is limited by the total number of times it is started.
   c. that results in no net saving in energy charges when load shedding is applied to it.

d. that results in a reduction in both energy charges and demand charges when load shedding is applied to it.

e. from which no savings can be recovered by load shedding.

9. The most effective method of power factor correction is ...

a. to let the power company do it at the substation.

b. to locate capacitor banks at major load centers.

c. to locate separate capacitors at every major inductive load.

d. true forecast load management.

e. to reschedule the operation of process equipment to better distribute the power load throughout the day.

10. The connected load is 600 kW. The power factor is 0.95. The demand is 400 kW. The billing period is 720 hours. The hours use of demand is 300 hours. In this case, the load factor is ...

a. 0.417.

b. 0.667.

c. 380 kW.

d. 2.4.

e. cannot be determined from the data given.

11. In the above problem, the average load for the billing period is ...

a. 400 kW.

b. 120,000 kWh.

c. 167 kW.

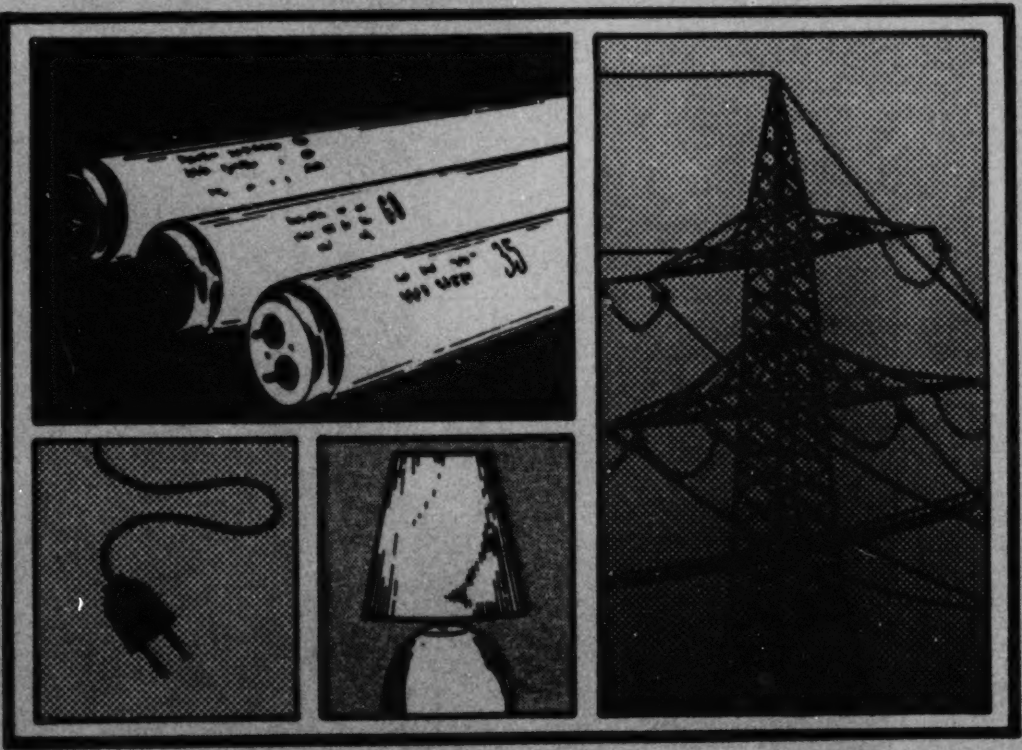
d. 250 kW.

e. cannot be determined from the data given.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-06

FUNDAMENTALS OF ILLUMINATION

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Illumination is the process of providing adequate light to perform a given task. The type and amount of light required depends upon the nature of light itself, the characteristics of the human eye and the visual process, and the nature and difficulty of the task to be performed. This module discusses each of these factors and its effect on illumination systems and the process of seeing.

Topics include the nature of light and characteristics of light sources, color vision, and the mixing of colors, factors affecting the visual process, units of measurement of light, measurement techniques, and the quality and quantity of light provided by good illumination systems. PI-06, "Fundamentals of Illumination," is designed to acquaint the student with the properties of good illumination and introduce terms and concepts used to describe light sources and illumination systems.

In the laboratory, the student will perform several illumination measurements.

PREREQUISITES

The student should have mastered basic physics and d.c. and a.c. circuit analysis. The student should have also taken, or be taking, Electromechanical Devices.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe how light is produced in each of the following types of light sources and describe the spectral output of each type:
   a. Incandescent
   b. Gas discharge
   c. Fluorescent
2. Describe each of the following characteristics of light behavior:
   a. Reflection
   b. Diffusion
   c. Transmission
   d. Refraction
   e. Absorption
   f. The inverse square law
3. Draw a graph showing the relative response of the human eye as a function of wavelength.
4. Explain additive color mixture and subtractive color mixture.
5. Explain the following terms as they apply to vision:
   a. Accommodation
   b. Adaptation
   c. Visual capacity
   d. Visual acuity
6. Explain the terms "visual task" and "visual environment."
7. Define the following terms:
   a. Luminous intensity
   b. Luminous energy
   c. Illumination

- d. Brightness
- e. Candlepower
- f. Lumen
- g. Footcandle
- h. Footlambert

8. Explain how to make the following measurements with a footcandle meter. Include other measuring equipment that may be required in each case.
   - a. Illumination of a surface
   - b. Candlepower of a light source
   - c. Reflectance of a surface
9. List the four factors that determine the difficulty of a visual task.
10. Draw a curve showing visual performance as a function of illumination for a typical visual task.
11. Define the following terms:
    - a. Quality of illumination
    - b. Direct glare
    - c. Indirect glare
    - d. Atmosphere
12. In the laboratory, use a footcandle meter to measure the following quantities:
    - a. Illumination of a surface
    - b. Candlepower of a light source as a function of direction
    - c. Reflectance of a surface

THE NATURE OF LIGHT

Vision is the process by which information concerning the surroundings is received as optical signals by the eye, converted to nerve impulses, and interpreted by the brain.

The visual process depends on the light reaching the eye, the functioning of the eye, and the activity within the brain. Each of these topics will be discussed in PI-06, "Fundamentals of Illumination."

Illumination may be defined in broad terms as "providing the necessary light for the visual process." Since the illumination process begins with light, this module begins with a brief discussion of the nature of light.

DEFINITION OF LIGHT

Light is radiant energy: It travels through space at a constant speed of 3×10^8 m/s in the form of oscillations in electric and magnetic fields. Thus, it is also called "electromagnetic radiation." The basic nature of light is described by the use of two theories that seem to be contradictory. However, both theories are necessary to fully explain light's behavior.

The wave theory of light says that light behaves as a wave as it travels through space, or through (or around) objects. Light has a wavelength and frequency, and the product of these two quantities is the speed of light. Since speed is constant, an increase in frequency is accompained by a decrease in wavelength. The discussions in this module will involve the wavelength only.

Visible light is not the only kind of radiant energy. Figure 1 shows the entire electromagnetic spectrum. The wavelengths are given in meters on the top chart and in nanometers (10^{-9} m) on the bottom chart. The only differences in different types of electromagnetic radiation is the wavelength and frequency. The basic nature of X-rays is the same as the basic nature of visible light and radio waves.

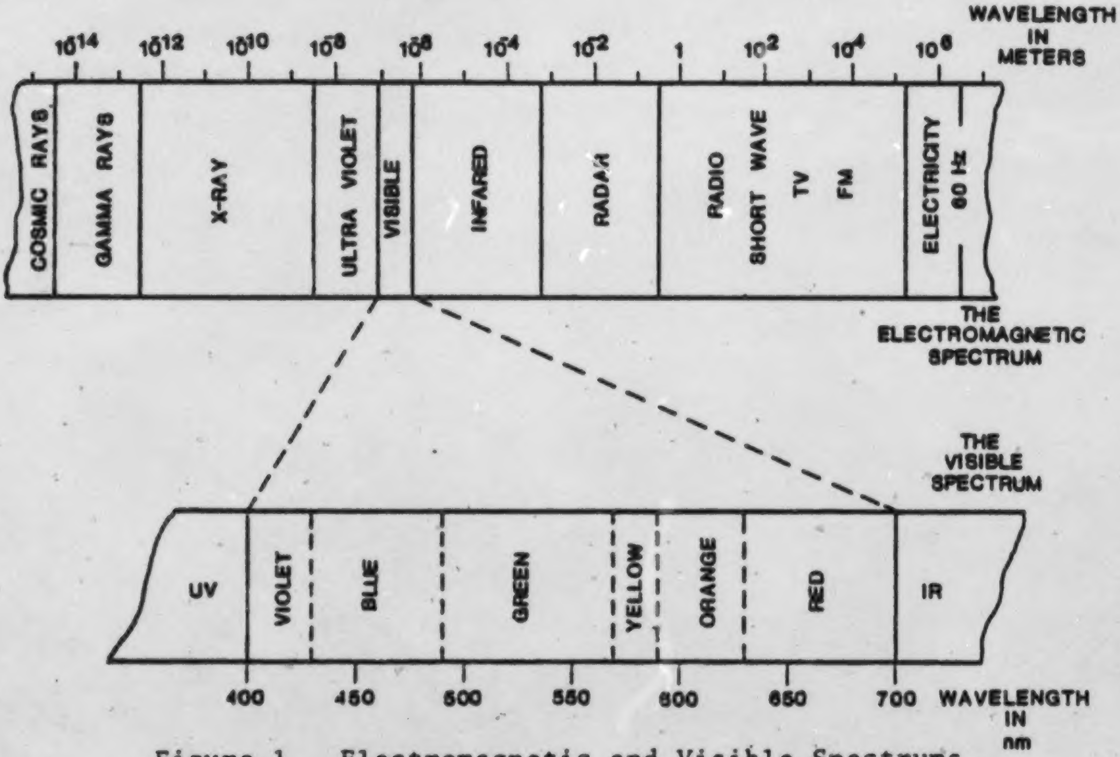

10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
WAVELENGTH IN METERS
COSMIC RAYS
GAMMA RAYS
X-RAY
ULTRA VIOLET
VISIBLE
INFARED
RADAR
RADIO
SHORT WAVE
TV
FM
ELECTRICITY
60 Hz
THE ELECTROMAGNETIC SPECTRUM
THE VISIBLE SPECTRUM
UV
VIOLET
BLUE
GREEN
YELLOW
ORANGE
RED
IR
400
450
500
550
600
650
700
WAVELENGTH IN nm

Figure 1. Electromagnetic and Visible Spectrums.

Visible light is actually only a tiny slice of the entire spectrum. Defined by the limits of the receptors in the human eye, visible light has a typical wavelength of 400 nm (nanometers) to 700 nm, although there are slight individual variations. The ultraviolet (UV) portion of the spectrum is a much broader spectral region, with wavelengths shorter than those of visible light. Another broad region, called the infrared (IR), has wavelengths longer than the wavelengths of visible light. Infrared radiation is detected by the skin as radiant heat. Light sources that produce visible light also produce UV and IR, although these wavelengths cannot be seen by the human eye.

The particle theory of light says that light behaves as a particle when it is produced or absorbed. The particle of light is called a photon.

Individual photons are emitted by individual atoms in the light source. Each travels in a straight line, unless deviated (as described later), and has the amount of energy given up by the atom to create the photon. Photons are also absorbed by individual atoms. The result is an increase in the atom's energy. The energy of each photon is proportional to the frequency of the light and, thus, inversely proportional to the wavelength. Shorter wavelength photons (blue) have more energy than longer wavelength photons (red).

Both the particle and wave theories are necessary to describe the behavior of light. The wave theory is used to describe the travel of light through space; the particle theory is used to describe emission and absorption processes.

GENERATION OF LIGHT

Light is produced when an atom in a high-energy state drops to a lower state and gives up some of its energy in the form of a photon.

Light sources vary both in the type of atoms used and the method employed to add the necessary energy to the atoms. Most light sources employ incandescent elements, gas discharges, or phosphorescent materials.

As the temperature of a material increases, the atoms in the material vibrate violently. Collisions between these atoms result in energy transfers that place some atoms in higher energy states. These atoms emit their excess energy in the form of photons. Hotter materials emit photons of shorter wavelengths.

Figure 2 shows the emission spectrum of a typical incandescent light operating at 2,800°C (60-watt bulb). This light emits light over a broad region of the spectrum; most

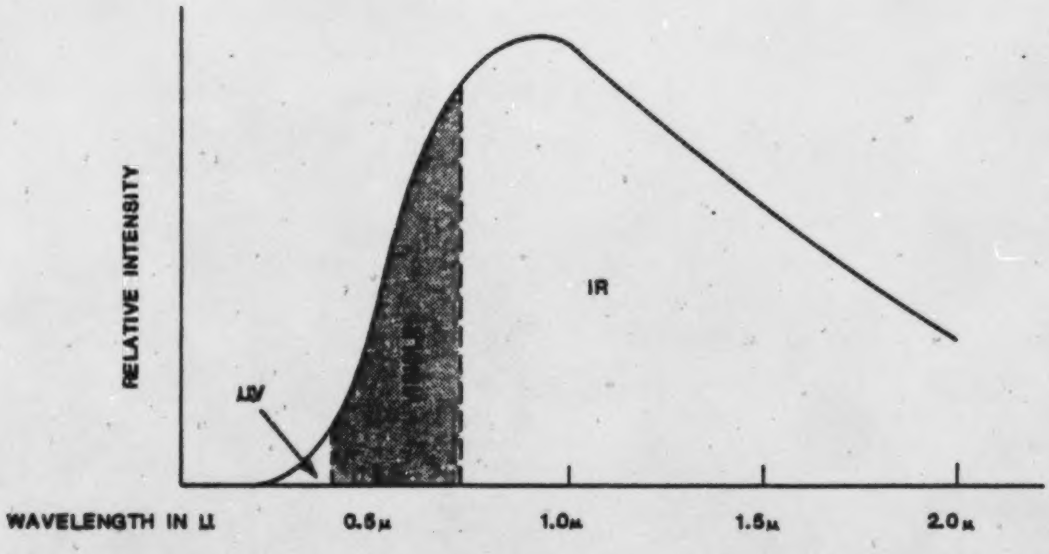


Figure 2. Spectral Energy Distribution of Incandescent Source.

of the energy falls in the infrared region. Such sources appear yellowish because the light they produce contains more of the longer wavelengths. At higher temperatures, incandescent sources appear first white and then blue because the peak of the emission curves shifts toward the blue end of the spectrum. Practical incandescent lamps cannot withstand the temperatures necessary to produce a large percentage of blue light.

Electric current is carried through a gas discharge by free electrons and positively charged ions. Energy is transferred to atoms and ions in the gas by collisions. These atoms and ions emit their excess energy as photons and drop to a lower energy state. This process occurs only between fixed energy levels that are characteristic of the atoms involved. Thus, most of the light is produced at a few predominant wavelengths. This results in poor color characteristics of most types of gas discharges because the light is not well-distributed in the visible spectrum. Much of the light produced by gas discharges often falls in the utltraviolet portion of the spectrum.

Fluorescence is an energy transfer process by which atoms absorb light of one wavelength and emit light of several longer wavelengths. Fluorescent lights are tubes containing a gas discharge and lined with materials called phosphors that absorb ultraviolet photons and re-emit the energy in the form of two or more visible photons (or possible visible and IR).

Figure 3 is the emission curve of a typical fluorescent lamp. The smooth portion of the curve represents the light emitted by the phosphor. The spikes are visible light emitted by the mercury-vapor discharge inside the tube. The ultraviolet light from this discharge excites the phosphor.

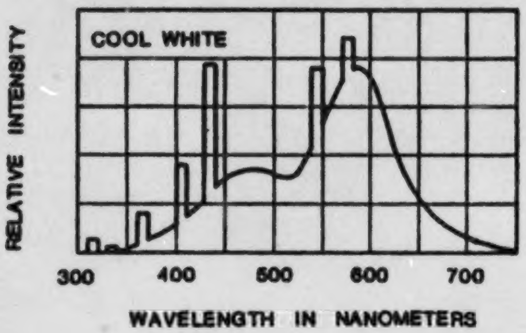


Figure 3.
Spectral Energy
Distribution of a Typical
Fluorescent Lamp.

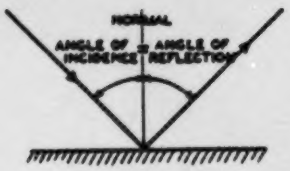
Fluorescent lighting is popular because it offers higher efficiency than incandescent lighting and better color qualities than gas discharge lighting.

All three types of light sources will be discussed in detail in Module PI-07, "Light Sources."

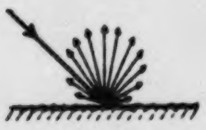
CHARACTERISTICS OF LIGHT BEHAVIOR

Figure 4 illustrates five characteristics of light behavior that are important in illumination applications. Figure 4a shows the reflection of light by a shiny surface such as a mirror or piece of glass. The normal line is a line perpendicular to the surface from which the angles of incidence and reflection are measured. These two angles are always the same. Such a reflection is called a specular reflection and does not scatter or disperse the light.

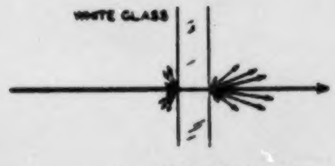
Figure 4b shows the diffuse reflection of light (also called diffusion) from a rough surface such as paper or wood. These surface are made up of many tiny reflecting surfaces


NORMAL
ANGLE OF INCIDENCE = ANGLE OF REFLECTION

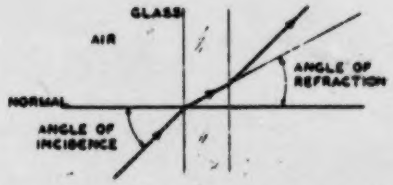
a. Reflection



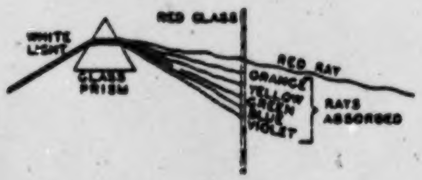
b. Diffusion


WHITE GLASS

c. Transmission


GLASS
AIR
ANGLE OF REFRACTION
NORMAL
ANGLE OF INCIDENCE

d. Refraction


RED GLASS
WHITE LIGHT
GLASS PRISM
RED RAY
ORANGE
YELLOW
GREEN
BLUE
VIOLET
RAYS ABSORBED

e. Absorbtion

Figure 4. Diagram of Light Characteristics.

at different angles and, thus, spread the reflected light in all directions. Most interior surfaces in buildings are diffuse reflectors.

Figure 4c shows the transmission of light through a clear material such as ordinary glass. A little of the light is scattered and reflected at the surfaces. However, most of the light is transmitted.

If the light strikes the transmitting material at an angle, as shown in Figure 4d, the light bends toward the surface normal. In this case, the angle of refractions is always less than the angle of incidence when the light enters the material. When the light leaves the material, it is refracted. The angle is increased. Refraction is the basis of lens operation.

Figure 4e shows the absorption of light by a material. White light is a mixture of all wavelengths (all colors). Most materials absorb some wavelengths but not others. In Figure 4e, the red glass absorbs all the shorter wavelengths, leaving only the red. Reflective materials, both specular and diffuse, reflect some wavelengths while they absorb others. The color of all materials depends upon what wavelengths are either reflected or transmitted.

THE INVERSE SQUARE LAW

The illumination provided by a light source on a surface depends on both the amount of light the source emits and the distance from the source to the surface being illuminated. Figure 5 shows a point source emitting the amount of light termed a "standard candle" (candela) in the direction of a surface one foot away.

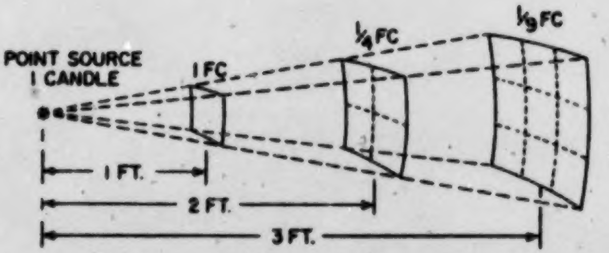


Figure 5.
Inverse Square Law.

The illumination of this surface is one footcandle (fc), the amount of illumination provided by a standard candle one foot away.

At a distance of two feet, the same amount of light is spread over an area four times as large. This produces an illumination of one-fourth as much, or 0.25 fc.

At a distance of three feet, the illumination drops to one-ninth the illumination at one foot. Thus, the illumination provided by any light source decreases in proportion to the inverse of the square of the distance from the source.

LIGHT AND COLOR

As previously implied, the color of any material as perceived by human vision depends upon both the light-absorbing properties of the material and the spectral distribution of the incident light. This section discusses how these characteristics of light and material — and the response of the human eye — result in color vision.

HUMAN EYE RESPONSE

Figure 6 shows the spectral response curve of a typical human eye. The eye is most sensitive at a wavelength of 555 nm, and the response drops off to effectively zero near 400 nm and 700 nm.

If light has an even distribution of energy across the visible spectrum, it is seen as white light. Light containing a predominance of one wavelength is seen as some variation of the color corresponding to that wavelength.

Figure 6 also shows the spectral characteristics of two light sources indivisible. Incandescent sources give all objects a slightly yellowish appearance. This is because of the high content of longer wavelengths. Natural daylight gives objects a more bluish appearance because daylight contains more light of shorter wavelengths.

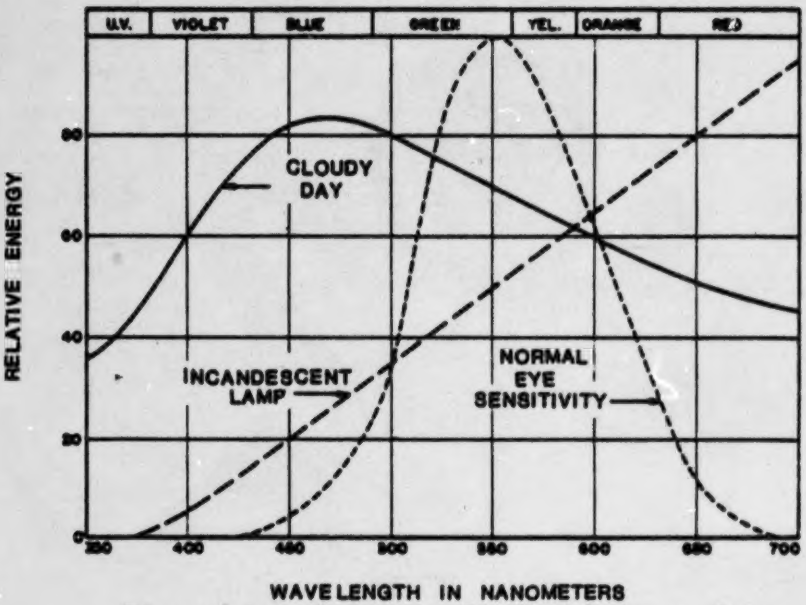


Figure 6. Response Curve of Human Eye.

NATURE OF COLOR VISION

The eye actually contains four different types of light sensors.

Rods operate only at very low light levels and have a peak sensitivity at 510 nm. Rods are responsible for night vision and cannot distinguish between colors. They operate only at illumination levels below the sensitivity of color vision and, thus, are of little interest in the field of illumination.

The receptors for color vision are three types of cones with peak sensitivities at 44 nm (blue), 535 nm (green), and 570 nm (red). Each of these cones also responds to other wavelengths but at lower sensitivity. Even a pure color results in some activity in all cases. The sensation of color is the result of all three types of cones working together.

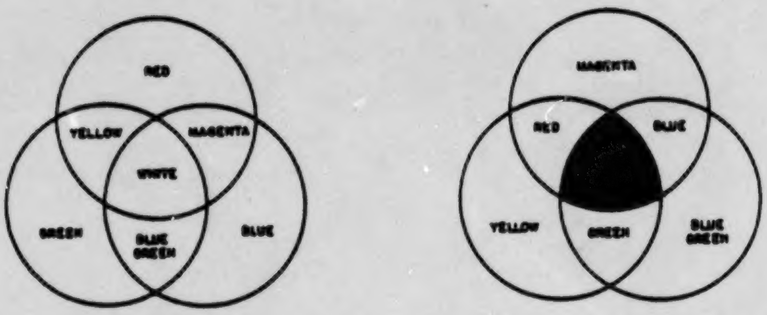
ADDITIVE COLOR MIXTURE

Additive color mixture is the creation of a new color by projecting two or more colors of light onto the same surface.

For example, red light and green light shining on a white card together will appear yellow. Red and a weak green will produce brown, since brown is actually very weak yellow. The additive primary colors are red, green, and blue. A white surface may be made to appear to be any color by mixing combinations of these three colors. Equal quantities of each produces light that looks white, although it does not contain all wavelengths in the visible spectrum.

Lighter colors, called tints, are produced by adding a little more of one or more of the primary colors. Pink, for example, is white light with a little extra red.

Color televisions contain three phosphors that produce the three additive primary colors and create all other colors by additive color mixture. Additive color mixture is used to produce white light in fluorescent and gas discharge light sources. Figure 7a illustrates additive color mixture.



a. Additive Primaries **b. Subtractive Primaries**

Figure 7. Additive and Subtractive Color Mixtures.

SUBTRACTIVE COLOR MIXTURE

Subtractive color mixture is the creation of a new color by filtering white light through two or more superimposed pigments or dyes. In this case, all colors may be created by combinations of the three subtractive primary colors – magenta, yellow, and blue-green.

Figure 7b illustrates subtractive color mixture. This is the process that produces the colors of all reflective objects. Subtractive color mixture depends upon the use of white incident light. If some combination other that white light is used for illumination, the colors will appear differently. This is one of the chief problems encountered when using gas discharge lighting.

Black and white pigments are not considered true colors. White pigments reflect all colors strongly, and black pigments absorb all colors. A pure color is a pigment that reflects only a narrow range of wavelengths well and absorbs all others. Pure colors appear to be bright, or vibrant.

White and black pigments are mixed with pure colored pigments to produce tints, as shown in Figure 8. Black and white mixed together result in gray, which may be mixed with a pure color to produce a tone of that color. The interior surfaces of most work areas are painted in lighter tints and tones to reflect most of the light for maximum illumination efficiency.

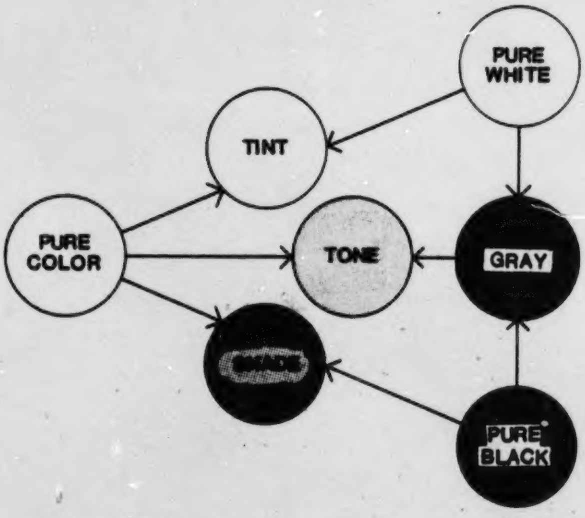


Figure 8. The Color Triangle.

THE VISUAL PROCESS

Obviously, the human eye is an important consideration when making illumination decisions. Of particular significance are the eyes' ability to adapt to varying light levels, the eyes' capacity to assimilate input, and the eyes' power to distinguish fine detail.

Attention must also be paid to the problems associated with aging and/or abnormal eyesight. The visual environment can be – and often must be – manipulated to accommodate the eyes' physiological structure.

THE HUMAN EYE

Figure 9 is a diagram of a human eye. Light enters the eye through the cornea, aqueous humor, and lens. Focusing of the eye is accomplished by both the aqueous humor and lens. The shape of the lens changes slightly to focus the images of objects on the retina according to distance. This process is called accommodation.

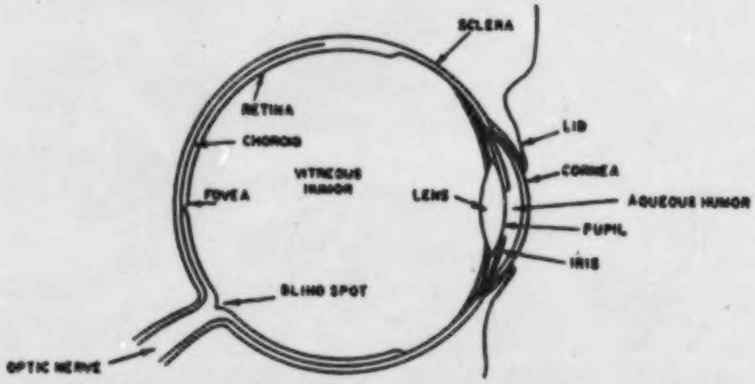

SCLERA
RETINA
CHOROID
VITREOUS HUMOR
FOVEA
LENS
LID
CORNEA
AQUEOUS HUMOR
PUPIL
IRIS
BLIND SPOT
OPTIC NERVE

Figure 9. The Human Eye.

At rest, the human eye is focused at about 200 feet. Today, most seeing tasks are performed approximately 14 inches from the eye. Long periods of close work fatigues the muscles that contract the lens of the eye and result in eye strain.

The iris of the eye is a ring of muscle just in front of the lens. This is the part of the eye that is responsible for eye color. The pupil is the hole in the center of the iris. The muscles of the iris increase and decrease pupil diameter to allow more or less light into the eye with changing illumination levels. The pupil also shrinks when the eye is focused on close objects. The smaller opening results in a sharper image on the retina for near objects. This adds to eye strain for close work under high illumination.

The imaging system of the eye produces images on the retina, a thin layer of cells on the back and side walls of the eye. The retina contains the rod and cone cells that change light signals into nerve signals. The highest concentration of cones is in the area called the fovea.

The fovea is the area of sharpest vision and is only a small part of the visual field, corresponding to the image of a circle 2 1/2 inches in diameter viewed from a distance of 10 feet. The clarity of vision drops off outside this area, but the total visual field for each eye has an angle of about 150°F. The total visual field of both eyes together is 180° in a horizontal plane and 140° in a vertical plane.

ADAPTATION

Adaptation is the ability of the eye to adjust to different levels of illumination. The pupil controls the amount of light entering the eye, but it can vary the light level by a factor of only about 16 to 1.

The most important part of adaptation takes place in the retina. Chemical changes in the light sensitive cells vary their sensitivity by a factor of about 1,000,000 to 1. This process involves the depletion and restoration of the light-absorbing pigments of the cells and is triggered any time the illumination level changes.

For abrupt changes, such as entering a dark theater from a sunny street, the adaptation of the cones takes about two minutes. Adaptation to lesser changes is accomplished more quickly, but this adaptation still involves a small time lag. Rod adaptation for night vision requires 30 to 40 minutes. Adaptation becomes important in the performance of visual tasks when the visual field contains areas of greatly varying brightness.

VISUAL CAPACITY

The eye does not respond instantly to a light stimulus, and the sensation of vision does not end abruptly when the stimulus is removed. Some time is required to build up an image and each image persists for a short time. Human vision actually consists of several still images sent to the brain each second. The rate at which the eye can assimilate information is called the visual capacity. Visual capacity is measured in assimilations per second (APS). The visual capacity automatically changes with changes in illumination level.

If a light source pulsates at a rate greater than the visual capacity, it is seen as a continuous source. Television and motion pictures consist of still images projected at a rate that exceeds the visual capacity of the eye. Fluorescent and gas discharge lamps pulsate at 120 cycles per second, but this rate is too fast to see. Visual discomfort and reduced visual acuity occur if the rate of light pulses is near the visual acuity rate.

VISUAL ACUITY

Visual acuity is the ability to discriminate fine details of objects within the central field of vision. Normal acuity is considered to be the ability to resolve details of an object that have a visual angle of one minute of arc. This is the angle created when a one-inch target is viewed from 100 yards.

Visual acuity is usually rated according to a test performed at a distance of 20 feet. A resolution of targets (openings in letters) of a little less than 0.1 inch at this distance is necessary for 20/20 vision, or an acuity of 1.0. A person who can resolve at this distance only those details that a normal eye can resolve at 40 feet has 20/40 vision, or an acuity of 0.5.

AGING AND ABNORMAL EYES

Although very few people are born with defective vision, about one third of the population wears corrective lenses. The performance of all eyes degrades with aging.

The lens of the eye never stops growing, but aging of the lens starts before birth. The lens becomes continually less flexible. The functioning of the iris also degrades with age and other parts of the eye are often affected. Visual acuity begins to drop at about 20 and continues to do so throughout life. Several types of abnormalities may occur in which visual acuity decreases at a higher rate.

Most tables of required illumination levels are based on minimum levels for the normal eye. Practical illumination design should always consider the below normal eye as well, and increase light levels accordingly.

THE VISUAL ENVIRONMENT

The visual environment consists of everything within the visual field. Even when a person concentrates on a particular task, the eyes constantly flicker away from the task to other portions of the environment. This extends the range of the peripheral vision to include the entire surroundings during every few minutes, even though people are seldom conscious of this.

Thus, the visual environment is usually considered to be everything that can be seen from a particular location. For optimum work efficiency, the illumination system should control the entire visual environment and not just provide the necessary illumination of the specific task.

UNITS OF LIGHT MEASUREMENT

The preceding sections of this module have discussed the characteristics of the visual process that acutally determine the required illumination levels and conditions for all visual tasks. This section presents the units of measurement used to describe and specify light quantities that are important in illumination.

LUMINOUS INTENSITY

Luminous intensity is the amount of light produced by a source in a specific direction. It is also called candlepower and is properly measured in units called candelas, although many references use only the term "candlepower."

Originally, one candlepower was defined as the amount of light emitted by one ordinary candle. The more constant modern standard is based on the light emitted from heated platinum.

Figure 10 shows a source that produces a luminous intensity of one candlepower in all directions. If a mirror were placed behind the source, its candlepower would be zero behind the mirror and would be greater than one in the forward

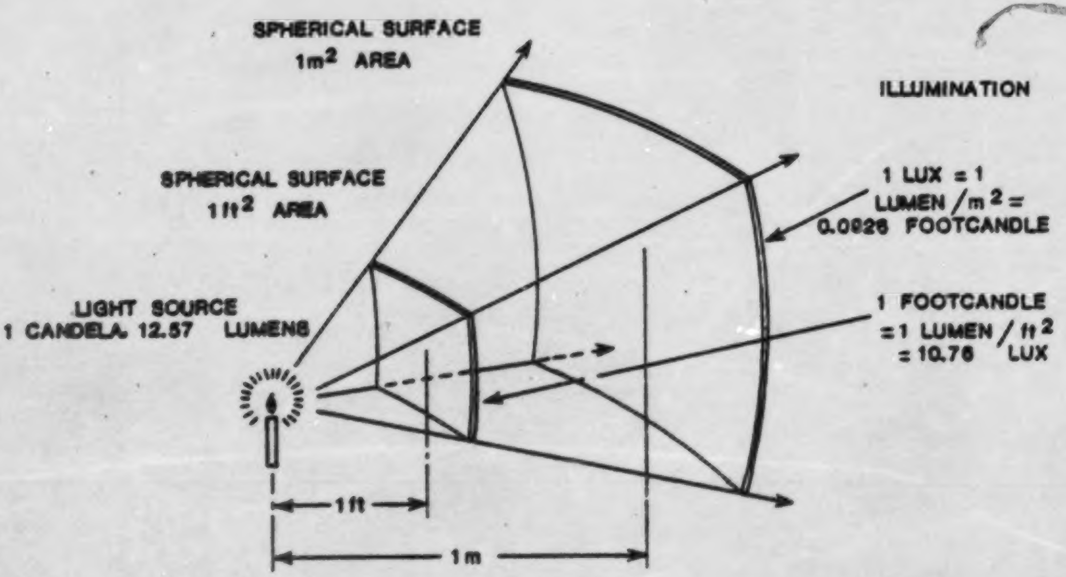

SPHERICAL SURFACE
1m² AREA
ILLUMINATION
SPHERICAL SURFACE
1ft² AREA
1 LUX = 1 LUMEN /m² = 0.0926 FOOTCANDLE
LIGHT SOURCE
1 CANDELA 12.57 LUMENS
1 FOOTCANDLE = 1 LUMEN / ft² = 10.76 LUX
1ft
1m

Figure 10. Units of Illumination.

direction. Candlepower is used to describe the directional qualities of both lamps and lighting fixtures. All light-measuring units are based on the candela.

LUMINOUS ENERGY

Luminous energy is the time rate of light flow. The unit of luminous energy is the lumen. The total amount of light produced by a source is measured in lumens.

A lumen is defined as the amount of light falling on a one-square-foot surface area where every point on that surface is one foot away from a source with a uniform luminous intensity of one candela. This is illustrated in Figure 10.

The total light energy falling on the one-square-foot area is one lumen. The total amount of light produced by the source in the figure is the amount falling on a complete sphere with a radius of one foot and the source at the center. The area of this sphere would be 12.57 square feet.

Thus, a uniformly-distributed source of one candela in all directions has a total luminous energy of 12.57 lumens. This does not mean that one candela equals 12.57 lumens. The candela is a measure of the strength of the light in a particular direction. The lumen is the measure of the total light emitted by the source.

ILLUMINATION

Illumination is the density of light falling on a surface. One footcandle is the amount of illumination produced by a one candela source one foot away, as illustrated in Figure 10. Thus, one footcandle is equal to one lumen per square foot.

The International System term for (metric, or SI units) unit of illumination is the "lux." Lux is the illumination level produced by a one candela source at a distance of one meter. Illumination meters may be calibrated in either footcandles or lux. Most modern meters have scales for both units.

The most important single factor in any illumination system is the illumination on the work surface. This is the total light striking the surface independent of direction. Minimum illumination levels are usually specified in footcandles. The illumination in footcandles provided by a source at any point can be determined by dividing the candlepower of the source in that direction by the square of the distance to the source in feet.

BRIGHTNESS

The unit of brightness is the footlambert and is defined as one lumen uniformly emitted or reflected from a surface of one square foot. The direction of the emitted light is unimportant.

Footlamberts are used in describing variations in brightness in the visual environment and in measuring glare. Footlamberts are not as commonly used as the other illumination units.

MEASUREMENT TECHNIQUES

The most common types of field measurements involving illumination systems are measurements made with an illumination meter, also called a footcandle meter. This meter employs a photocell that is equipped with a filter that gives it the same response curve as the human eye. A diffuser plate in front of the cell spreads the incoming light over the face of the cell. This gives an accurate illumination measurement independent of the direction of the incident light. Such meters are said to be color and cosine-corrected. This section explains the use of such instruments for field measurements of illumination.

MEASUREMENT ILLUMINATION

Footcandle meters indicate the illumination of the detector surface in footcandles. Thus, for an accurate indication of the illumination of a surface, the meter detector should be positioned so that it is as near that surface as possible and is parallel to the surface. Thus, if the illumination of a drafting table is to be measured with the table mounted at an angle of 30°, the meter should also be held at an angle of 30°.

MEASUREMENT OF CANDLEPOWER

The luminous intensity of a source in a particular direction may also be measured using a footcandle meter. The meter is held at a convenient distance from the source with its detector facing the source for normal incidence of light. The illumination at that point is measured in footcandles. The distance from the detector to the source is measured in feet.

The candlepower of the source (in the direction from the source to the detector) is the illumination in footcandles divided by the square of the distance in feet. By taking a series of measurements at several angles around a source, a graph of candlepower versus direction may be drawn.

MEASUREMENT OF REFLECTANCE

The reflectance of a surface may be estimated by the use of a footcandle meter, although more sophisticated techniques are required for great accuracy.

One measurement method is to determine surface illumination by placing the meter as close to the surface as possible with the meter detector parallel to the surface. The illumination produced by light reflected from the surface is then measured by directing the meter toward the surface, while being sure that no shadow is cast on the surface by either the meter or the person holding it. The meter detector must also be shielded from light from any direct sources. The approximate reflectance of the surface is the second reading divided by the first.

A more accurate measurement of reflectance can be accomplished by comparing the reflected light from a surface of unknown reflectance with the light reflected from a surface of known reflectance under similar conditions.

The meter is first positioned to indicate the illumination produced by reflection from the surface of unknown reflectance. With the meter in the same position, a card of known reflectance is placed against the surface and the illumination produced by light reflected from the card is measured. The card must be large enough to effectively fill the field of view of the meter.

If an 8 by 10-inch card is used, the measurements should be made no further than about two inches from the surface. The reflectance of the unknown surface is calculated by dividing the illumination from that surface by the illumination from the card and multiplying the result by the reflectivity of the card.

QUANTITY OF ILLUMINATION

The illumination system for any visual task must produce the necessary level of light on the task. This section describes factors affecting the illumination levels necessary to accomplish various visual tasks.

THE VISUAL TASK

The visual task is the sum total of all the things that must be seen at any given time.

Complex tasks involve several visual tasks, and the illumination level required is based on the most difficult task. The difficulty of the visual task is dependent on four factors: the size of the detail to be seen, the time available for the seeing, the contrast between the detail and its background, and the brightness of the task.

The brightness of the task depends upon both the level of illumination and the reflectivity of the task. Figure 11 shows the illumination level (footcandles) necessary for a person with normal eyes to assimilate the required information at a rate of five APS.

SEEING TASK	FOR 5 APS
2 PENCIL — MAT WHITE PAPER	63
3 PENCIL — STENOGRAPHIC NOTES	76
FOURTH CARBON TYPED COPY	133
TRACING CLOTH OVER BLUEPRINT	266
ORANGE CHALK ON BROWN TWEED	400
BROWN STAIN ON GREY CLOTH	1100
BROWN STAIN ON RED NECKTIE	2400
BROKEN BLACK THREAD ON BOBBIN	2900

Figure 11. Footcandles Required for 5 APS — Representative Tasks.

VISUAL PERFORMANCE

Visual performance curves, such as those shown in Figure 12, indicate how the performance of visual tasks improves with increased illumination. All visual task curves have the same shape. Curves for tasks of higher difficulty are located farther to the right in the figure. For each task there is an illumination level below which the task cannot be performed and a level above which increased illumination makes no difference.

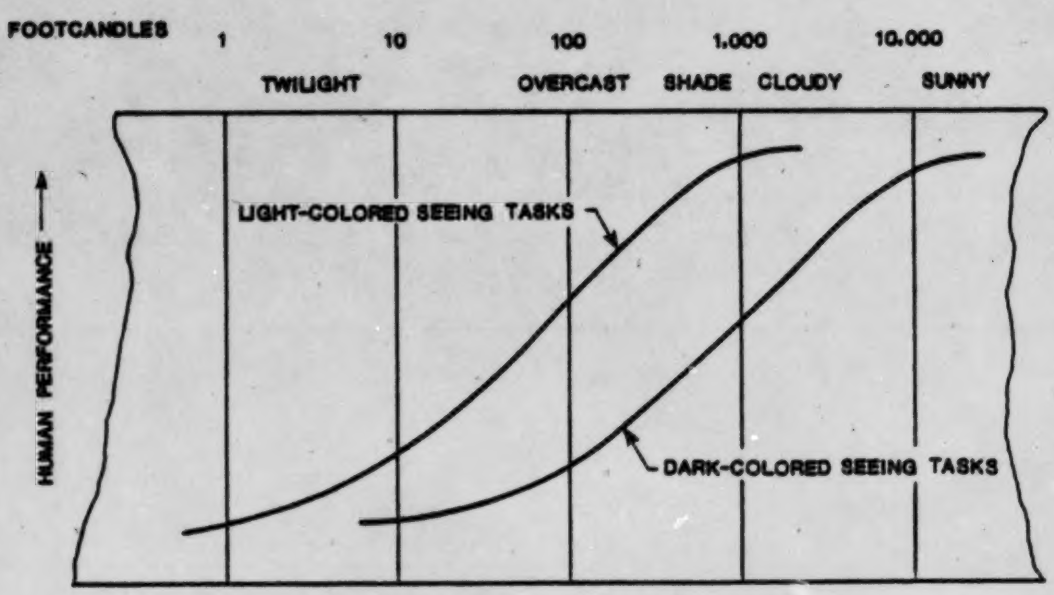


Figure 12. Effects of Lighting Level on Human Performance.

Between these two extremes is a range over which performance rises with illumination. Illumination systems should be designed to provide light levels giving the highest performance level for the task. Tables of minimum recommended illumination are available covering hundreds of tasks. The following are a few representative recommendations:

Corridors, elevators, and stairways	20 fc
Cafeterias	50 fc
Classrooms	70 fc
Detailed drawing and drafting	200 fc
Fine inspection and assembly	500 fc

QUALITY OF ILLUMINATION

Illumination quality is also a factor in the performance of visual tasks. Quality refers not to the amount of light present on the task, but to the distribution of brightness in the visual environment and the color of the light and surfaces present.

BRIGHTNESS DISTRIBUTION

The distribution of brightness in the visual environment has an effect on the performance of all visual tasks. Both dark areas and light areas may have a detrimental effect. This is because momentarily looking in each direction results in the adaptation of the eye to that brightness level, instead of the brightness of the task. The person must then wait for adaptation back to the brightness level of the task. The brightness ratio of the task to the immediate surroundings of the task should never exceed 3 to 1. The brightness ratio between the task and any part of the visual environment should never exceed 10 to 1.

Glare is produced by areas of high brightness in the visual field. Direct glare results when the light source is in the field of view; indirect glare is the result of reflections of the light from the source by shiny surfaces. Glare may not interfere with the lighting on the task, but it reduces visual performance because it causes discomfort. Good lighting systems are always designed to reduce glare to a minimum.

ATMOSPHERE

The term "atmosphere" refers to the "feel" of the visual environment. It is not a measureable quantity and depends on the psychological effects of patterns of brightness and color. The maximum lighting efficiency is achieved when all surfaces are white. This also reduces the brightness ratio between the task and the surroundings.

However, the sterile appearance of a colorless environment is usually unpleasant after a short time. Light tints and tones for walls and areas of color increase environmental pleasantness without a great reduction in reflected light. The selection of surface colors in interior spaces is a common method of setting a particular mood. Other factors are the selection and placement of light sources and the overall level of illumination. Each lighting system must be designed to provide the proper level of illumination within the environment in which it is installed.

SUMMARY

Illumination is concerned with providing the proper visual environment for the performance of a specific visual task. The most important aspect of the illumination system is that it provides adequate illumination of the task, but other factors should also be considered.

Illumination should be delivered to the work surface without the presence of objectionable glare. The remainder of the environment should be designed to have a brightness near that of the task, while still providing some variations.

The following specifications are the most important units used in in illumination.

- Illumination is measured in footcandles. One footcandle is the illumination provided by a candle at a distance of one foot. It is a measure of light per surface area.
- Luminous intensity is measured in candelas or candlepower. It is a measure of the amount of light leaving a source in a particular direction.
- Luminous energy is the total light energy produced by a light source measured in lumens.

EXERCISES

1. Draw graphs showing the following as functions of wavelenths:
   a. Colors of the visible spectrum
   b. Human eye response
   c. Output of an incandescent lamp
   d. Output of a fluorescent lamp
2. Explain the following terms as they apply to human vision:
   a. Adaptation
   b. Accommodation
   c. Visual Capacity
   d. Visual acuity
3. A light source as a uniform luminous intensity of 100 candlepower. Determine the following:
   a. Light output in lumens
   b. Illumination on a surface 5 feet from the source
   c. Illumination on a surface 10 feet from the source
   d. Total luminous energy striking a one-square-foot area 20 feet from the source
4. Define the following characteristics of light behavior:
   a. Reflection
   b. Diffusion
   c. Transmission
   d. Absorption
   e. Refraction
5. Describe additive and subtractive color mixture. List the primary colors of each. Give an example of each.
6. Define the following terms:
   a. Direct glare
   b. Indirect glare
   c. Atmosphere

LABORATORY MATERIALS

Footcandle meter

8 by 10-inch card of known reflectivity (white paper may be used with an assumed reflectivity of 90%)

LABORATORY PROCEDURES

This laboratory exercise consists of measuring the illumination levels and the reflectivity of surfaces in a variety of visual environments.

1. Use the footcandle meter to measure the illumination on a variety of surfaces. Record the nature and location of each surface and the measured illumination in Data Table 1. Take measurements on at least 20 surfaces in a variety of environments. Include measurements in following locations if possible:
    - Outdoors in direct sun
    - Outdoors in shade
    - Hall
    - Several points in laboratory
    - Office space
    - Shop facility
2. Use the footcandle meter, the white card, and the comparison method of reflectivity measurement, to measure the reflectivity of at least 5 different surfaces under different lighting conditions. Record the nature of the surface, its location, and its reflectivity in Data Table 2.

DATA TABLE 1. ILLUMINATION MEASUREMENT.

Surface and location	Illumination (fc)
1.	
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	
11.	
12.	
13.	
14.	
15.	
16.	
17.	
18.	
19.	
20.	

DATA TABLE 2. REFLECTION MEASUREMENTS.

Surface and location	Reflectivity (%)
1.	
2.	
3.	
4.	
5.	

REFERENCES

Fundamentals of Commercial and Industrial Lighting. The Electrification Council. N.W. Washington, DC: 1977.

Helms, Ronald N. Illumination Engineering for Energy Efficient Luminous Environments. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1980.

Nuckolls, James L. Interior Lighting for Environmental Designers. New York, NY: John Wiley and Sons, 1976.

Please circle the appropriate answer.

1. The total light power produced by a source may be measured in ...
   - a. footcandles or lumens.
   - b. lumens or candelas.
   - c. footlamberts.
   - d. lumens.
   - e. None of the above are correct.
2. A light source produces an illumination of 100 fc at a distance of 10 feet. The illumination produced by the same source at a distance of 20 feet is ...
   - a. 100 fc.
   - b. 50 fc.
   - c. 25 fc.
   - d. 100 candlepower.
   - e. The answer cannot be determined with the data given.
3. In the direction towards the surface with an illumination of 100 fc, the light source in the above question had a luminous intensity of ...
   - a. 1 candlepower.
   - b. 10 candlepower.
   - c. 100 candlepower.
   - d. 1,000 candlepower.
   - e. 10,000 candlepower.
4. Incandescent light sources usually ...
   - a. produce a spectral distribution that closely approximates daylight.
   - b. produce very little ultraviolet light.
   - c. produce very little infrared light.
   - d. None of the above are correct.
   - e. Only b and c are true.

5. Subractive color mixture ...
   - a. is the process used in color television.
   - b. depends on the primary colors red, blue, and green.
   - c. is effective, regardless of the incident light.
   - d. produces white light when all colors are mixed together.
   - e. None of the above are correct.
6. Adaptation of the human eye ...
   - a. is the change of shape of the lens for focusing on near objects.
   - b. is accomplished primarily by changes in pupil diameter.
   - c. is accomplished primarily by chemical changes in the retina.
   - d. refers to night vision only.
   - e. None of the above are correct.
7. Quality of illumination is not affected by ...
   - a. large variations in brightness in the visual environment that are not near the location of the visual task.
   - b. light sources within the field of vision.
   - c. a reduction of illumination on the task.
   - d. painting all surfaces white.
   - e. None of the above are correct.
8. The proper illumination in a typical classroom is approximately ...
   - a. 20 fc.
   - b. 100 fc.
   - c. 500 fc.
   - d. 10 fc.
   - e. 1,000 fc.

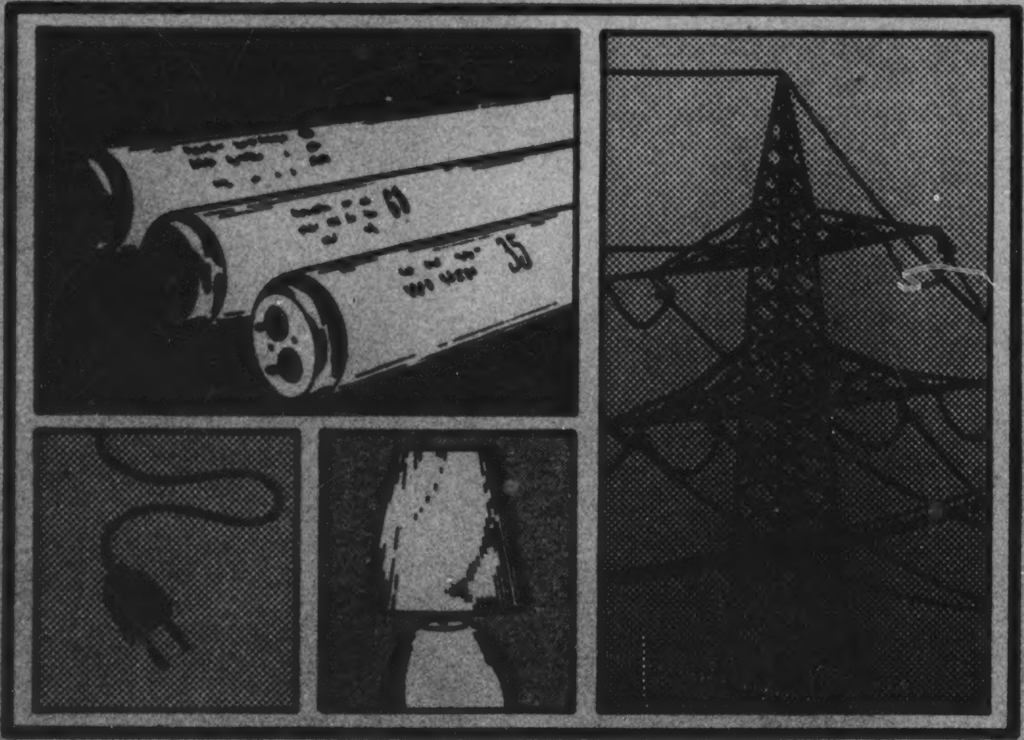
9. The difficulty of a visual task is determined by ...
   a. the size of details to be viewed.
   b. the time available for viewing.
   c. the reflectants of the objects to be viewed.
   d. All of the above are correct.
   e. Only a and b are correct.

10. Light with a wavelength of 450 nm is the color ...
   a. blue.
   b. green.
   c. yellow.
   d. red.
   e. The resulting color cannot be seen by the human eye.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-07
LIGHT SOURCES

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Increasing energy costs in recent years have led to greater awareness of the costs associated with illumination. Spiraling costs have spawned an ever-increasing interest in more efficient illumination systems. Several new types of light sources have been developed and become popular. Additional light sources will be available shortly.

PI-07, "Light Sources," discusses the characteristics of sources that affect the overall cost of illumination systems. Cost characteristics include the efficiency of the source in producing light, the lifetime of the source, the rate at which the source degrades with time, and the color characteristics of the light produced.

Incandescent, fluorescent, high-intensity discharge, and low-pressure sodium lamps are discussed and evaluated according to these criteria. The advantages and disadvantages of each source are also discussed. In the laboratory, the student will measure the candlepower of several sources and plot candlepower distribution curves.

PREREQUISITES

The student should have completed Module PI-06, "Fundamentals of Illumination."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain the following terms applied to light sources:
    a. Efficacy
    b. Efficiency
    c. Spectral energy distribution
    d. Lumen depreciation
    e. Lifetime
2. Describe the lamp construction, spectral energy distribution, efficacy, lifetime, and lumen depreciation for each of the following lamp types:
    a. Incandescent
    b. Fluorescent
    c. Mercury-vapor
    d. Metal halide
    e. High-pressure sodium
    f. Low-pressure sodium
3. Describe the changes that occur in the output of each of the above lamps with variations in line voltage.
4. Explain the purpose of a lamp ballast.
5. Explain the starting procedures for the following lamps:
    a. Mercury-vapor
    b. High-pressure sodium vapor
    c. Rapid-start fluorescent
6. Explain the term "light control" as it applies to illumination systems.
7. In the laboratory, measure the candlepower of several sources as a function of angle around the source.

CHARACTERISTICS OF LIGHT SOURCES

Four characteristics may be used to compare the operation of various light sources. These characteristics are spectral energy distribution, efficacy, lumen depreciation, and mortality.

SPECTRAL ENERGY DISTRIBUTION

The spectral energy distribution (SED) curve of a light source is a graph of relative light output versus wavelength. This curve shows the strongest wavelengths in the output light and indicates the color characteristics of the source. Sources approximating white light are usually preferred over strongly-colored sources for most applications. The spectral energy distribution curves of all common light sources are included in this module.

EFFICACY

The light output of a source is measured in lumens. The electrical input energy is measured in watts. The efficacy of a source is the ratio of lumens to watts and is stated in lumens per watt. Efficiency of the source is output power at visible wavelengths (in watts) divided by the input electrical energy (in watts).

Efficacy is a good indicator of the performance of light sources, since the lumen is defined according to the response of the human eye. A source that converts most of its energy to visible light at either the extreme red or extreme blue wavelengths has a high efficiency. However, its efficacy is low, since the eye does not respond well to those wavelengths. Thus, efficacy – rather than efficiency – is a better measure of the useful light produced by the source for each watt of electrical energy consumed. Both the efficiencies and efficacies of all common light sources are given in this module.

LUMEN DEPRECIATION

The output of a light source is specified in lumens. This specification may be the initial luminous energy of a new source, or the luminous energy of the source after a specified length of operation.

In either case, the luminous energy produced by a source, and thus its efficacy, decreases with total operating time. This is called lumen depreciation and the rate varies with the type of source. Typical lumen depreciations of common sources are given in this module.

MORTALITY

Lamp mortality describes the average expected lifetime of a lamp before failure occurs. Figure 1 is a typical lamp mortality curve for incandescent lamps. Curves for other types of lamps have the same general shape. The rated life of a particular lamp is the time in which one half of the lamps of that type have failed during normal operation during testing. Thus, half of the lamps are expected to fail before their rated lifetime, and half will continue to operate

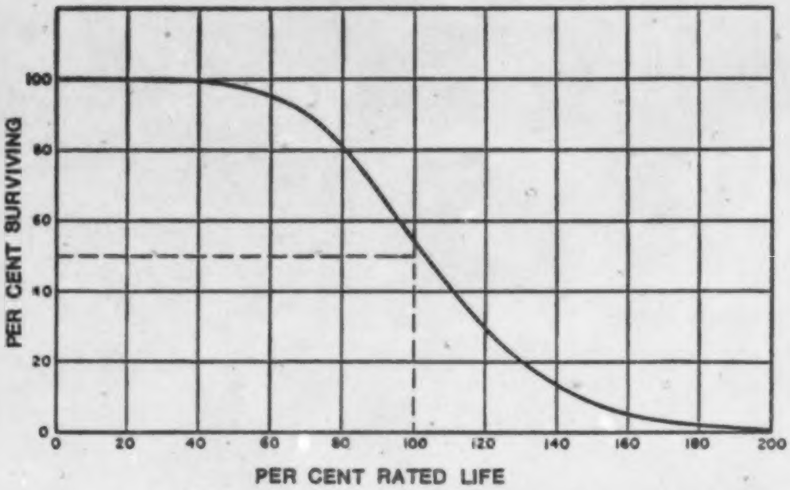


Figure 1. Average Mortality Curve for a Group of Incandescent Filament Lamps.

beyond their rated lifetime. About half of the failures normally occur within 20% of the rated lifetime. Lumen depreciation often indicates lamp replacement before the rated lifetime. The rated lifetimes of common lamps are given in this module.

INCANDESCENT LAMPS

The following material centers on the construction, spectral energy distribution, and lamp characteristics of incandescent lamps.

LAMP CONSTRUCTION

Figure 2 shows the basic construction of a common incandescent lamp. This is the oldest type of electric lamp and the incandescent lamp is still the most popular lamp for residential use. It produces light from a tungsten filament heated by current flow. The filament is coiled to reduce heat losses to the gas filling the lamp bulb; the filament is

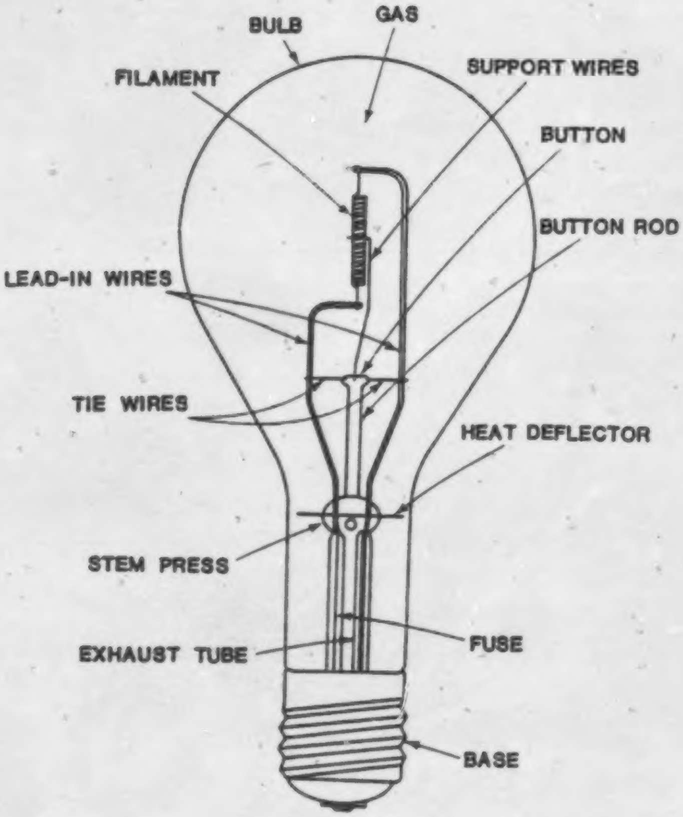

BULB
GAS
FILAMENT
SUPPORT WIRES
BUTTON
BUTTON ROD
LEAD-IN WIRES
TIE WIRES
HEAT DEFLECTOR
STEM PRESS
EXHAUST TUBE
FUSE
BASE

Figure 2. Incandescent Lamp.

cradled by the lead-in and support wires. The light output and spectral energy distribution of the lamp depend on the filament temperature.

The bulb of the lamp is lime glass in general illumination lamps, but other materials are used for specific applications. The bulb may be clear, but the unobstructed view of the tungsten filament offers objectional glare. Most bulbs have a diffuser surface. This may be achieved by etching the inner surface with acid, coating the inner surface with white silica, or coating the outer surface with a white ceramic.

The glass bulb contains gas that reduces the evaporation of the filament material. In common lamps, the gas is argon. Extended life and improved efficacy may be achieved with krypton, but this rare gas is so expensive that only specialty bulbs employ it. Each bulb also contains a small amount of nitrogen to eliminate internal arcing.

Lumen depreciation occurs because of deposits of filament material on the glass bulb. Lumen depreciation is greatly reduced in quartz-halogen lamps. Quartz-halogen lamps contain a small amount of iodine that vaporizes during operation and causes most of the filament material to condense back on the filament.

Incandescent lamps are available in a wide range of types, sizes, and shapes. Some are equipped with internal reflectors that concentrate most of the light in a specific direction or pattern.

SPECTRAL ENERGY DISTRIBUTION

Figure 3 shows the spectral energy distribution curves for two incandescent lamps with two different filament temperatures. Most incandescent sources fall between these two extremes.

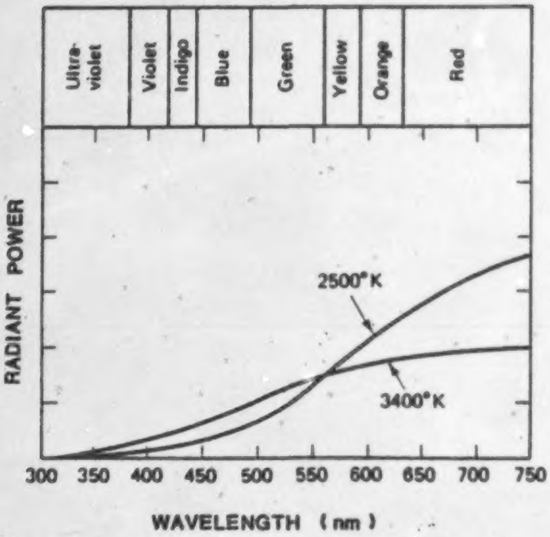


Figure 3. Spectral Energy Distribution for an Incandescent Lamp.

In all cases, the output contains considerably more red light than blue. Thus, incandescent sources produce a yellowish or "warm" atmosphere. Even so, incandescent lamps provide acceptable color rendition. Incandescent illumination is so common that most people accept the colors produced by it to be natural, even though the light produced is considerably different from daylight.

LAMP CHARACTERISTICS

The characteristics of incandescent lamps vary greatly with the size and design of the lamp. The efficacy generally increases with lamp wattage. The efficacy of a 60-watt bulb is 14.3 lumens/watt. The efficacy of a 100-watt bulb is 17.5 lumens/watt. Large wattages (1,000 to 10,000 watt) have efficacies in the range of 20 to 30 lumens/watt. Lower-voltage bulbs generally have higher efficacies. This is because lower-voltage bulbs have larger diameter filaments for the same wattage and, thus, more light-emitting area.

Light output of incandescent bulbs usually decreases by about 20% during the bulb's rated lifetime. Lifetimes vary from as short as 75 hours for large special-purpose lamps, to as much as 2,500 hours. Lower-wattage lamps usually have longer lives. A typical 100-watt lamp has a rated life of 750 hours; the life of a 60-watt lamp is usually over 1,000 hours.

Krypton fill extends the lamp's life to about 3,000 hours. Quartz-halogen lamps have about twice the lifetime and half the lumen depreciation of ordinary incandescents. Lamp efficacy increases with increased voltage, but the lifetime of the lamp drops. Low voltage operation reduces efficacy and increases lamp life.

Figure 4 shows the energy distribution of an ordinary 100-watt incandescent bulb. Only 10% of an incandescent bulb's input energy appears as visible light. Efficacy is further lowered because most of this light is on the red end of the spectrum and not in the green-yellow region where the eye is most sensitive. Seventy-two percent of the input energy appears as infrared (heat) radiation. The remaining 18% heats the bulb and its fixture.

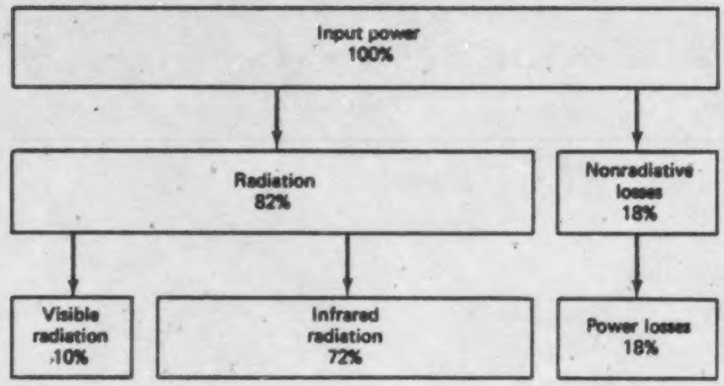

Input power
100%
Radiation
82%
Nonradiative
losses
18%
Visible
radiation
10%
Infrared
radiation
72%
Power losses
18%

Figure 4. Energy Distribution of an Incandescent Lamp.

All energy consumed by the light source eventually appears as heat in the lighted environment. Even that part of the energy that is converted to visible light is changed to heat when it is absorbed by surfaces.

FLUORESCENT LAMPS

The following material centers on the construction, electrical characteristics, spectral energy distribution, and lamp characteristics of fluorescent lamps.

LAMP CONSTRUCTION

Fluorescent lamps are long glass tubes filled with mercury vapor. A small amount of argon or argon-neon gas is added to increase electrical conductivity before the mercury is fully vaporized. Atomic transitions in the mercury atoms produce light at several visible and ultraviolet (UV) wave lengths.

The inner wall of the glass tube is coated with a phosphor that allows the visible light to pass through, but absorbs the UV and converts it to visible light by fluorescence. The electrodes of the lamps are called cathodes and may be either "cold" metal plates or "hot" coils of wire.

Most fluorescent lamps employ the heated cathode. This cathode may be heated by a separate heater circuit or by current flow through the gas. Fluorescent lamps are available in a wide range of sizes, but the most common are the four-foot lamp, rated at 40 watts, and the eight-foot lamp, rated at 110 watts. High output models provide higher wattage and more light per foot of length, but high output models are usually less efficient.

ELECTRICAL CHARACTERISTICS

All gas discharge devices require a ballast to limit the current. Otherwise, high current surges would soon destroy the device. The most common type of ballast for fluorescent lamps is an inductor in series with the lamp. This produces a lagging power factor for many fluorescent lighting systems. Some modern lamp ballasts employ both inductors and capacitors in the ballast circuit to provide either a balanced power factor or a slightly leading power factor.

Several methods may be used to start fluorescent lamps. Older lamps employed a separate starter that heated the cathode to operating temperature before the operating voltage was applied to the lamp. Once the lamp is in operation, the cathode heater circuit is turned OFF. Instant-start lamps have no separate cathode heater circuit. To start the lamp instantly, a high-voltage pulse heats the cathode and initiates the discharge.

The latest type of lamp starting, and the one used in most modern installations, is rapid-starting. Rapid-start lamps have low resistance cathodes that can be heated continuously during lamp operation with low power losses. The heater circuits of the cathodes are turned ON at the same time as the main discharge. The lamp dose not light until the cathode temperature has reached the proper level. This usually takes one to two seconds. Lamps designed for one type of starting system should, in general, not be used with another type of starting system, although there are some exceptions.

SPECTRAL ENERGY DISTRIBUTION

Fluorescent lamps are available with several different spectral distributions depending on the phosphor used for the tube coating. Figure 5 shows the spectral energy distribution curves of six of the most common lamp types. All types contain the strong spectral lines characteristic of mercury-vapor discharges.

Cool white lamps are often selected for offices, factories, and commercial areas where a psychologically cool working environment is desired. This is the most popular fluorescent lamp.

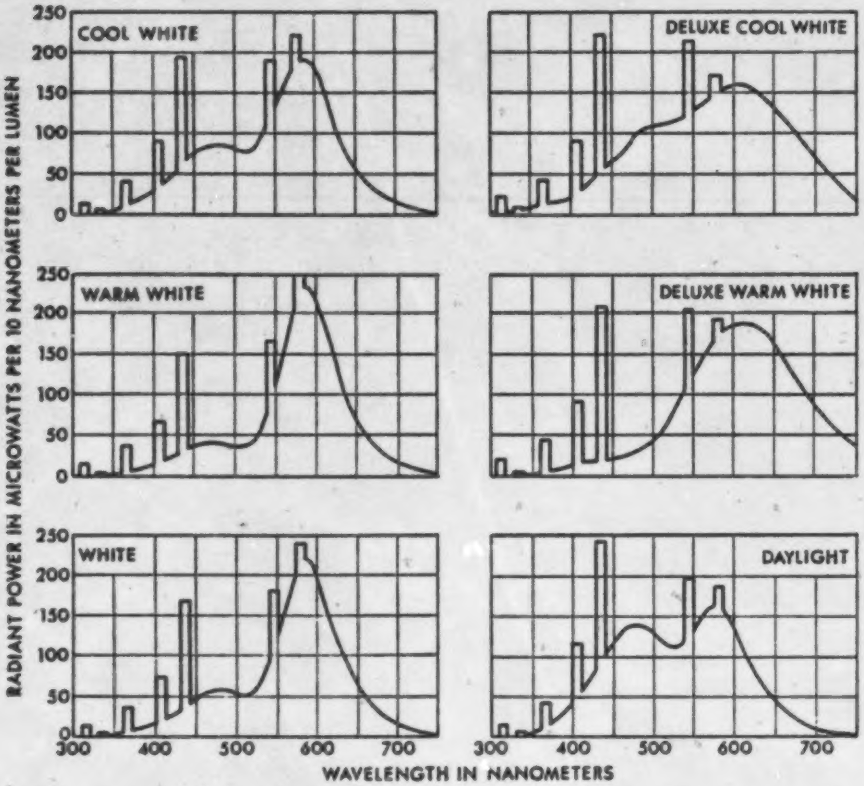


Figure 5. SED Curves – Typical Fluorescent Lamps.

The deluxe cool white is used for the same general applications, but produces more red light and is, therefore, more flattering to the appearance of people and merchandise. It has the best color rendition of any fluorescent.

Warm white fluorescent lamps are designed to have a color spectrum close to that of incandescent lamps. These lamps are used whenever a warm social environment is desired.

Deluxe warm white lamps have an additional red element that more closely approximates the appearance of incandescent lighting. Deluxe warm white lamps more flattering to the appearance of people and are recommended for use in homes and social areas.

White fluorescent lamps are used for general lighting purposes when neither a warm nor a cool atmosphere is to be created. They produce more light in the green, yellow, and orange portions of the spectrum and are a little more efficient for general illumination. Daylight bulbs are designed to produce an effect close to that of natural daylight. The spectrum is fairly well-balanced, but contains more blue light than red.

LAMP CHARACTERISTICS

The efficacies of all fluorescent lamps are higher than for any incandescents. They range from 40 lumens/watt to 80 lumens/watt with an average of about 60 lumens/watt. The light output of fluorescent lamps drops by about 10% during the first 100 hours of operation. After that, the drop is much more gradual. For this reason, the lumen output of these lamps is specified at 100 hours of operation. Lumen depreciation depends primarily on lamp current. Standard lamps will typically depreciate only about 10% in 10,000 hours of operation. High-current models may drop by 40% in the same time.

Fluorescent lamps are not as sensitive to voltage variations as incandescents, but fluorescent lamps are still affected by voltage variations. Overvoltage operation increases the current in both the lamp and the ballast. This overheats the ballast and increases the lumen depreciation of the lamp.

Undervoltage operation reduces light output and efficacy. If the voltage is low enough, the cathode may run too cool and be damaged. Fluorescent lamps are designed to operate most efficiently with wall temperatures of 100°C and lamp efficacy drops on either side of this temperature. Fluorescent lamps must, therefore, be protected from drafts and air flow from air conditioners.

The lifetime of a fluorescent lamp is limited primarily by the number of lamp starts. Starting the lamp degrades the cathode coating, and after a sufficient number of starts, the lamp will no longer function. Lamp starting also degrades the phosphor coating and increases lumen depreciation.

In most cases, the lamp is degraded to an uneconomical light output before it actually fails. Lifetime ratings vary with the average time the lamp is ON each time the lamp is started. At an average of three hours of operation for each start, most fluorescent lamps have a lifetime of 9,000 to 12,000 hours. This is much greater than the lifetime of any incandescent lamp. Special precautions must be taken if fluorescent lamps are to be operated in an environment where the relative humidity exceeds 65%.

Figure 6 shows the energy distribution of a typical 40-watt fluorescent lamp. The nonradiative losses include the power necessary to heat the cathode and losses in the ballast. About 22% of the input energy is converted to visible light. Since the spectral distribution is usually better than that of incandescents, efficacy is generally three or four times as great. Thus, a 40-watt fluorescent lamp produces almost 40% more useful illumination than a 100-watt incandescent. A 40-watt fluorescent lamps also lasts about 20 times as long as a 100-watt incandescent lamp.

Another attractive advantage of fluorescent lamps is their large light-emitting area at low brightness. This greatly reduces discomfort glare. Fluorescent lighting is the most popular and economical type for indoor areas where color rendition is important.

Several manufacturers have been conducting research on fluorescent lamps that are direct replacements for incandescent bulbs. These are small fluorescent lamps with internal ballasts and screw bases to fit ordinary lamp sockets. Small fluorescent lamps that fit traditional lamp sockets are expected to be available in early 1981 in sizes from 9 to 26 watts. The efficacy is about 50 lumens/watt and the rated lifetime is 5,000 to 7,500 hours.

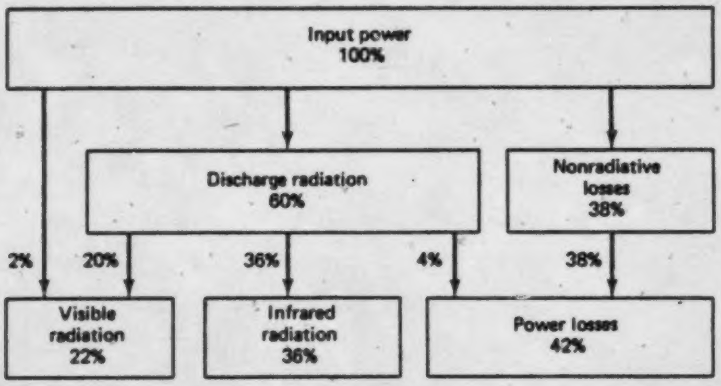

Input power
100%
Discharge radiation
60%
Nonradiative losses
38%
2%
20%
36%
4%
38%
Visible radiation
22%
Infrared radiation
36%
Power losses
42%

Figure 6. Energy Distribution for a Fluorescent Lamp.

HIGH-INTENSITY DISCHARGE (HID) LAMPS

The following material centers on high-intensity discharge lamps. Topics include mercury-vapor lamp construction, metal halide lamp construction, spectral energy distribution, and lamp characteristics of HID lamps.

MERCURY-VAPOR LAMP CONSTRUCTION

Figure 7 shows the construction details of a high-intensity discharge, mercury-vapor lamp. The arc tube of this lamp contains a small pool of liquid mercury that is vaporized during operation to produce a mercury pressure of several times atmoshperic pressure. The arc tube is made of quartz to withstand the operating temperature of about 1,000°C. Like all gas discharge lamps, the mercury lamp requires a ballast to limit current. Some ballasts include transformers that change the line voltage to the lamp operating voltage. Others incorporate capacitors for power factor correction.

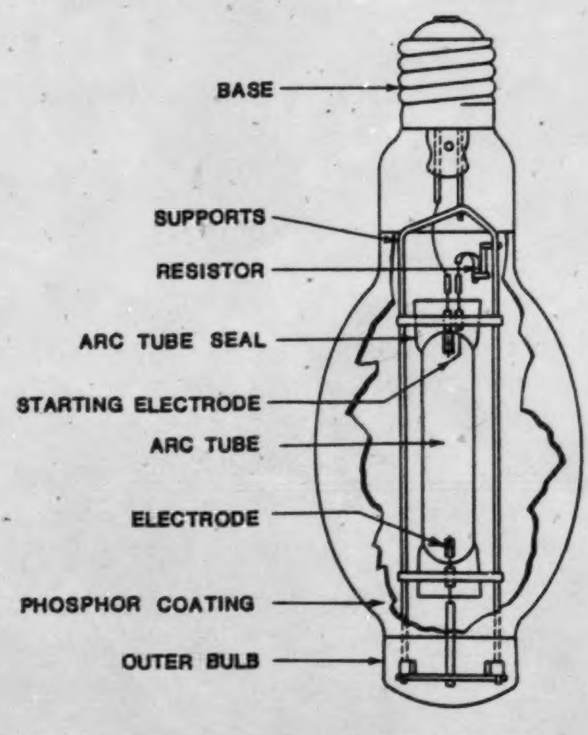

BASE
SUPPORTS
RESISTOR
ARC TUBE SEAL
STARTING ELECTRODE
ARC TUBE
ELECTRODE
PHOSPHOR COATING
OUTER BULB

Figure 7. Mercury-Vapor Lamp and Arc Tube.

The mercury lamp is started by a small arc produced between the starting electrode and one of the main electrodes. This heats the lamp to vaporize the mercury and ignites the main discharge. Lamp warmup takes from four to seven minutes. The outer bulb of the mercury lamp serves several purposes. It absorbs harmful ultraviolet wavelengths, retains heat to maintain the proper operating temperature of the arc tube, and may be coated with a phosphor that converts some of the UV light into visible light. Mercury lamps may be operated in any position, although vertical mounting results in three to four percent more light output.

METAL HALIDE LAMP CONSTRUCTION

Metal halide lamps are similar to mercury-vapor lamps in construction and operation. The arc tubes of these lamps contain mercury, but they also contain halides (usually iodides) of other metals. Sodium, scandium thallium, and indium may be used.

Because of a more complicated arrangement of the starting electrodes, metal halide lamps can be operated in only one position. Models for horizontal mounting have arc tubes that curve upward in the middle to better distribute the heat of the arc over their surface. The starting and operating characteristics are similar to those of the mercury lamps.

SPECTRAL ENERGY DISTRIBUTION

Figure 8 shows the spectral energy distribution curves of two types of mercury-vapor lamps. The mercury vapor

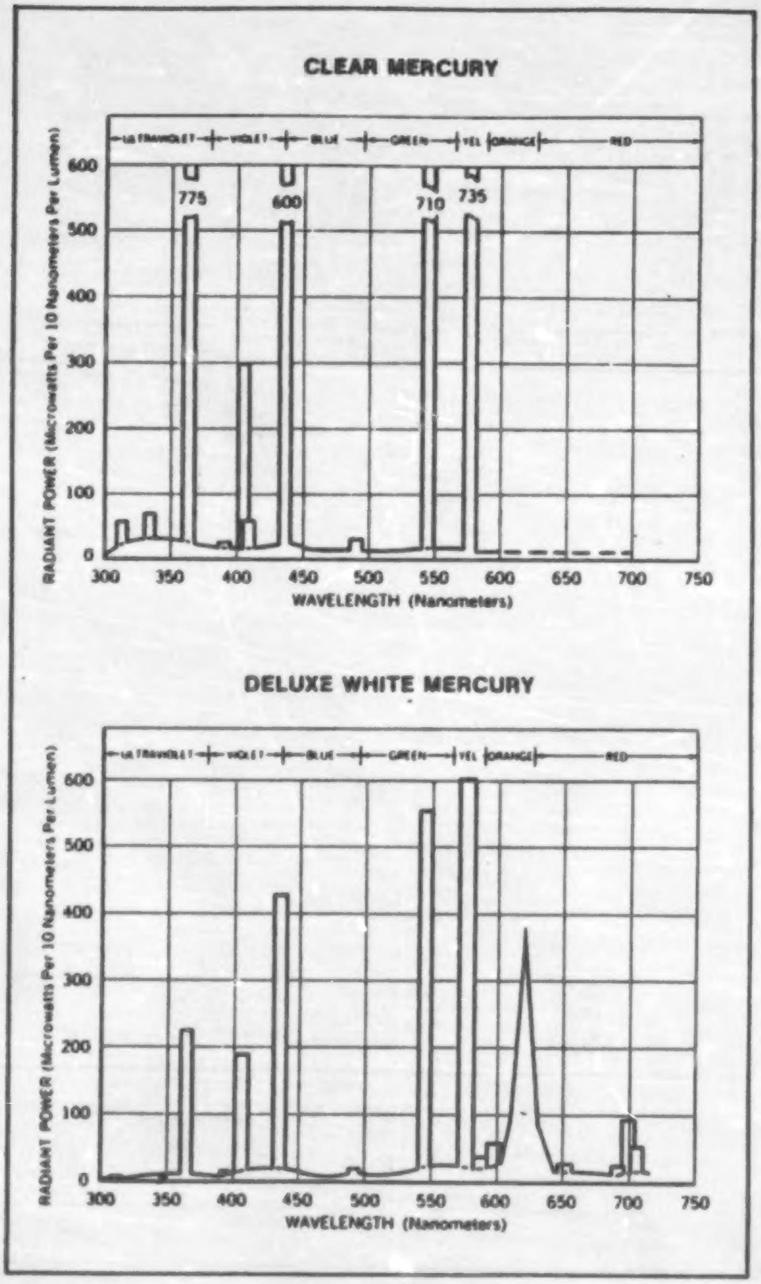


Figure 8. SED Curves for Mercury-Vapor Lamps.

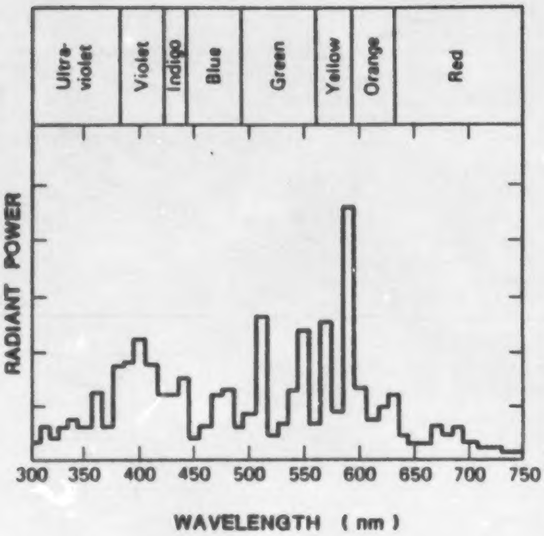
discharge emits most of its light on the four strong visible wavelengths shown and on six wavelengths in the UV.

In the clear mercury lamp, the UV is absorbed by the outer bulb and only the visible light is used. Several types of mercury lamps are available that employ phosphors to convert some of the UV into visible radiation for better efficacy and color rendition.

If the total lumen output and color rendition are the only factors considered, the coated lamps are far superior. However, if the light source is a large distance from the surface to be illuminated, light control becomes important. Clear mercury lamps are small sources and their light can be easily controlled for long-distance application, such as in outdoor sports stadiums. Coated mercury lamps are much larger sources and can be used only for more diffuse, more close applications.

Figure 9 is the output spectrum of a typical metal halide lamp. These lamps produce some light at all wavelengths in the visible spectrum and, thus, provide good color rendition when they are operating properly. Metal halide lamp color characteristics vary considerably with operating temperature and, thus, with voltage. At lower than rated voltage, the lamp temperature is below normal and less of the sodium is vaporized. This results in less red and yellow light and a strong blue appearance. At overvoltages, too much sodium is vaporized and the color becomes pink. Color also varies with lamp age, and if color characteristics are important, all lamps in a system should be replaced at the same time.

Figure 9. Spectral Energy Distribution for Metal Halide Lamp.



HID LAMP CHARACTERISTICS

Like fluorescent lamps, the output of HID lamps is rated at 100 hours of operation because of early, rapid, lumen decreciation. The efficacy of mercury lamps is usually 50 to 60 lumens/watt. Metal halide lamps have efficacies as high as 80 lumens/watt. Mercury lamps have rated lifetimes in excess of 25,000 hours. Metal halide lamps have lifetimes of 10,000 hours or a little less. In both cases, lumen depreciation is a more likely reason for replacement than lamp failure

The output of mercury-vapor lamps drops to about 80% of the rated value after 10,000 hours of operation. After 20,000 hours, output is only about 60% of the original. Metal halide lamps reach these same values in about half the time.

Some mercury-vapor lamp systems have automatic light level control that adjusts for lumen depreciation. A photocell controls voltage to the lamps. When the lamps are new and have the highest efficacy, they are operated on reduced voltage. This saves energy and increases lamp life.

As lamps age and efficacy drops, the voltage needed to maintain desired illumination is increased. In such systems, all lamps should be replaced at the same time. Metal halide lamps cannot be used in mercury-vapor lamp systems because of their sensitivity to voltage changes.

Figure 10 shows the energy distribution of a mercury lamp. The mercury lamp actually converts less of its total

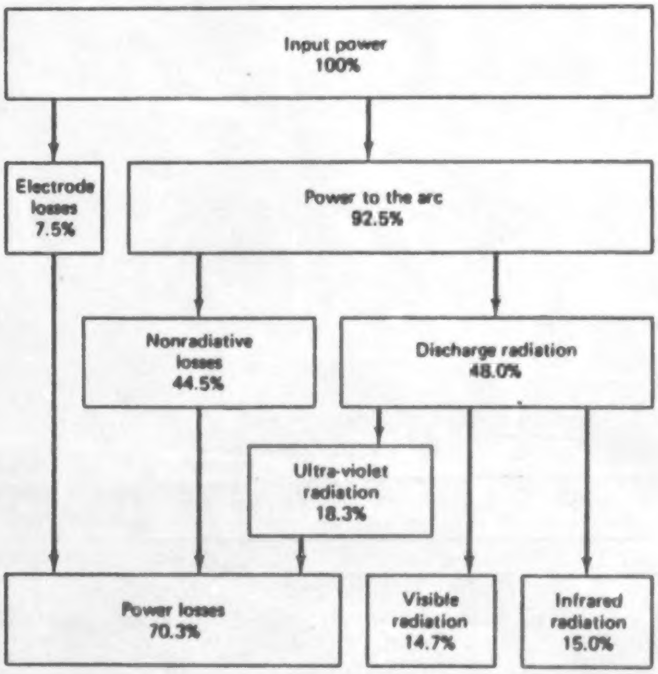

Input power 100%
Electrode losses 7.5%
Power to the arc 92.5%
Nonradiative losses 44.5%
Discharge radiation 48.0%
Ultra-violet radiation 18.3%
Power losses 70.3%
Visible radiation 14.7%
Infrared radiation 15.0%

Figure 10. Energy Distribution for Mercury-Vapor Lamps.

input energy to visible light than the fluorescent lamp. However, mercury lamp efficacy is higher because most of its light is at wavelengths to which the eye is very sensitive. This further illustrates the need to consider the efficacy of the source, rather the efficiency.

Figure 11 is a similar chart for a metal halide lamp. Its energy conversion efficiency of electrical energy to visible light is only slightly greater than that of fluorescent lamps. However, the spectral energy distribution of a metal hide lamp is such that the light it produces is more easily seen than the light of a fluorescent lamp.

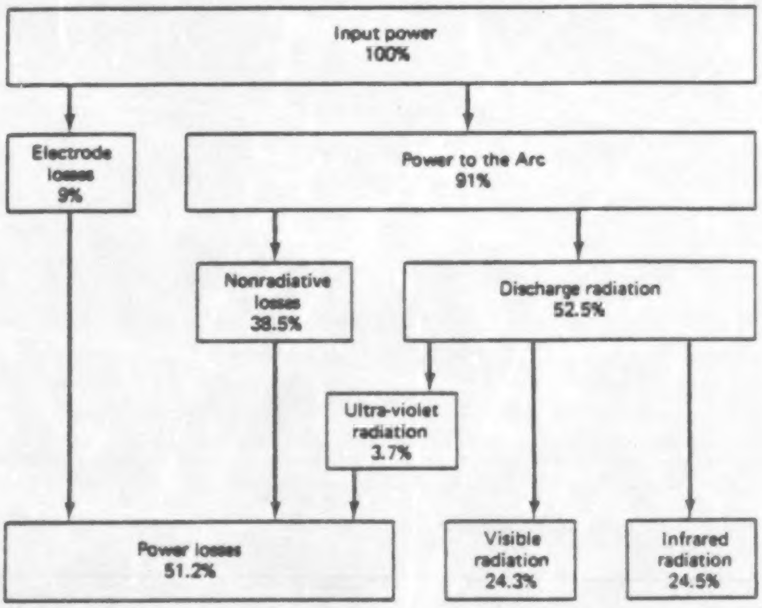

Input power
100%
Electrode losses
9%
Power to the Arc
91%
Nonradiative losses
38.5%
Discharge radiation
52.5%
Ultra-violet radiation
3.7%
Power losses
51.2%
Visible radiation
24.3%
Infrared radiation
24.5%

Figure 11. Energy Distribution for Metal Halide Lamp.

HIGH-PRESSURE SODIUM LAMPS

The following material explains the construction, spectral energy distribution, and lamp characteristics of high-pressure sodium lamps.

LAMP CONSTRUCTION

The construction of a high-pressure sodium lamp is similar to that of a mercury lamp, but the sodium lamp contains no starting electrode or resistor. The arc tube is made of a special form of translucent aluminum oxide that can withstand the corrosive sodium vapor at high temperature (up to 1,300°C). The small diameter of the arc tube helps to maintain the high temperature necessary, but leaves no space for a starting electrode. Starting is accomplished by a circuit in the ballast.

In addition to sodium, the arc tube contains xenon gas and mercury. A pulser circuit in the ballast supplies 2,500 V pulses that ionize the xenon. The xenon arc slowly heats the arc tube to the point that the mercury begins to vaporize.

At this point in the starting process, the lamp has the bluish-white color of a mercury lamp. As the temperature increases, the sodium vaporizes and the spectrum shifts to the monochromatic yellow that is characteristic of a low-pressure sodium discharge. When the lamp reaches its normal operating temperature, its spectrum broadens to include other wavelengths. The operating pressure is about 200 mm of mercury. The lamp is termed "high pressure" because its pressure is much greater than that of the low-pressure sodium lamp discussed in the next section.

The starting process requires about three minutes. If a sodium lamp is turned OFF, it may be restarted in about one and one-half minutes. A mercury lamp, however, has a restrike time of about five minutes.

SPECTRAL ENERGY DISTRIBUTION

Figure 12 is the spectral energy distribution curve for a high-pressure sodium lamp. These lamps produce light at all visible wavelengths, but most of their radiation is in the yellow-orange range. This gives them their characteristically high efficacy (140 lumens/watt), but results in poor color rendition.

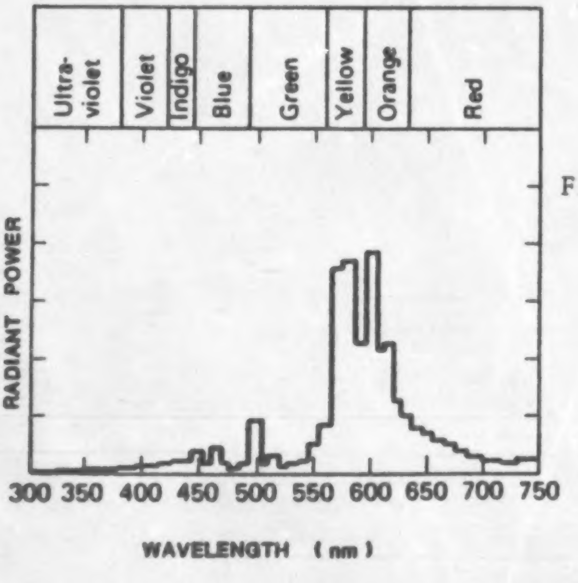


Figure 12. Spectral Energy Distribution for High-Pressure Sodium Lamp.

Blue and green objects appear very dark. Red objects appear orange. Tints of yellow and orange cannot be distinguished from white. Therefore, the color characteristics of high-pressure sodium lamps make them unsuitable for most indoor illumination applications.

LAMP CHARACTERISTICS

High-pressure sodium lamps have typical efficacies of 110 to 130 lumens/watt, with some models reaching 140 lumens/watt. The lifetime ratings vary from 15,000 hours to 24,000 hours. As the lamp ages, its required voltage rises. Eventually, the lamp exceeds the voltage capabilities of the ballast and the lamp will no longer operate. The lumen depreciation is the lowest of any high-intensity discharge lamp. Most high-pressure sodium lamps produce 80% of their rated output at the end of their lives.

Figure 13 is an energy distribution diagram for a high-pressure sodium lamp. Its high efficiency and spectral distribution gives it the highest efficacy of any lamp that can be used for general illumination. The long life and retention of high efficacy of a high-pressure sodium lamp makes it a popular light source for any applications for which it is suited. The high-pressure sodium lamp is widely-used for outdoor and street illumination.

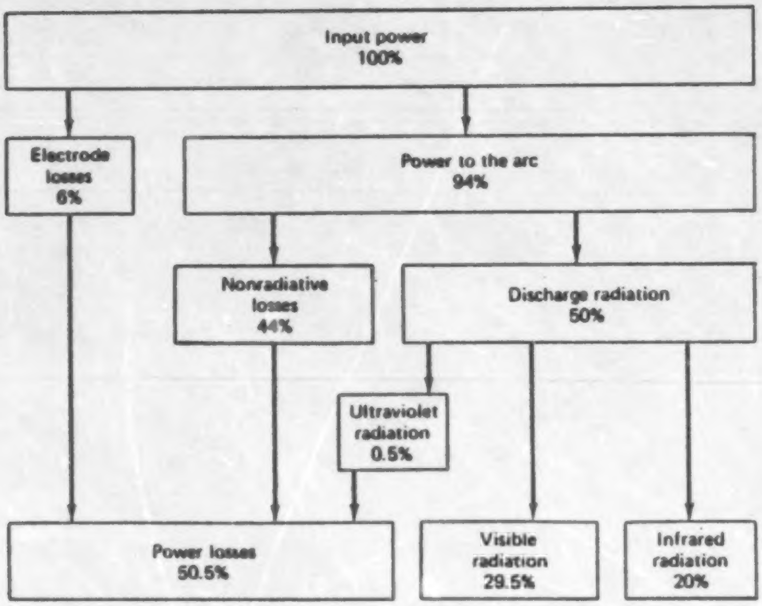

Input power
100%
Electrode losses
6%
Power to the arc
94%
Nonradiative losses
44%
Discharge radiation
50%
Ultraviolet radiation
0.5%
Power losses
50.5%
Visible radiation
29.5%
Infrared radiation
20%

Figure 13. Energy Distribution for the High-Pressure Sodium Lamp.

LOW-PRESSURE SODIUM LAMPS

The following material explains the construction, spectral energy distribution, and lamp characteristics of low-pressure sodium lamps.

LAMP CONSTRUCTION

Figure 14 shows the basic construction of a low-pressure sodium lamp. These lamps are available in the power range of 35 to 180 watts, with lengths of 12 to 44 inches. The U-shaped discharge tube is lined with borate to withstand the sodium vapor.

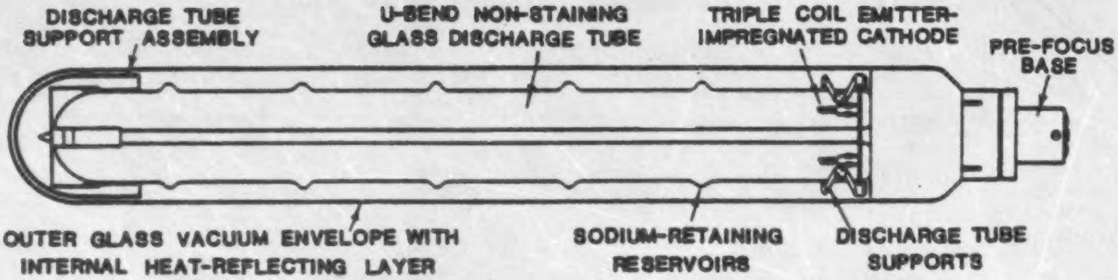

DISCHARGE TUBE SUPPORT ASSEMBLY
U-BEND NON-STAINING GLASS DISCHARGE TUBE
TRIPLE COIL EMITTER-IMPREGNATED CATHODE
PRE-FOCUS BASE
OUTER GLASS VACUUM ENVELOPE WITH INTERNAL HEAT-REFLECTING LAYER
SODIUM-RETAINING RESERVOIRS
DISCHARGE TUBE SUPPORTS

Figure 14. Low-Pressure Sodium Lamp Parts.

Swellings in the tube contain small amounts of sodium. The tube contains a neon-argon mixture for starting. The outer tube of the lamp is internally coated with indium oxide. This allows the visible light to escape, but reflects infrared light back into the lamp to maintain heat and conserve energy. A vacuum between the two tubes prevents heat loss through conduction, as in other gas discharge lamps.

SPECTRAL ENERGY DISTRIBUTION

All light output of low-pressure sodium lamps is produced at approximately 589 nanometers (nm). Light is a slightly orange hue of yellow. This wavelenth is seen easily by the human eye, resulting in a high efficacy. However, the monochromatic (one color) characteristic of this source makes it unsuited for applications that require an ability to distinguish between colors.

LAMP CHARACTERISTICS

Low-pressure sodium lamps have an efficacy of 183 lumens/watt (lamp only) and maintain this efficacy throughout their rated lifetime of 18,000 hours with little lumen depreciation. Figure 15 is an energy distribution chart for a typical low-pressure sodium lamp. The low-pressure sodium lamp has the highest efficiency and efficacy of any light source known. These lamps have existed for about 40 years, although not with the present efficacy.

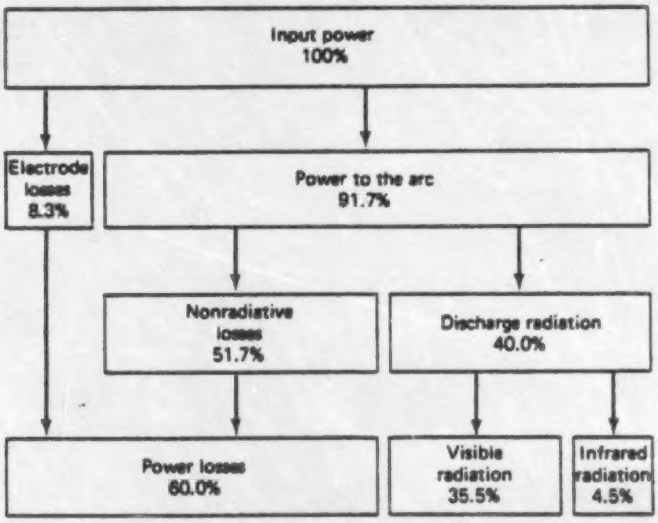

Input power
100%
Electrode losses
8.3%
Power to the arc
91.7%
Nonradiative losses
51.7%
Discharge radiation
40.0%
Power losses
60.0%
Visible radiation
35.5%
Infrared radiation
4.5%

Figure 15. Energy Distribution of a Low-Pressure Sodium Lamp.

Low-pressure sodium lamps have been largely ignored because of their poor color-rendering characteristics. Recent concerns with energy costs have sparked renewed interest in low-pressure sodium lamps for applications in storage areas, equipment rooms, and television monitoring areas. Low-pressure sodium lamps are the most economical light source for applications that require no color discrimination.

COMPARISON OF LAMPS

Table 1 lists the specifications for several light sources that are availabe. Values for efficacy are calculated using the input power to both lamp and ballast for all gas discharge lamps.

Corrected efficacy values for the lamp lumen depreciation over the lamp lifetime are also given, as are values with respect to a 100-watt incandescent lamp as 1.0. The rated lifetime of each lamp has been included.

This table compares only efficacy and lifetime and cannot be used alone as a lamp selection guide. Color-rendering characteristics of lamps are usually of great importance. These characteristics are not included in this table.

TABLE 1. LIGHTING EFFICACY OF VARIOUS LIGHT SOURCES.

		Lumens/Watt			Corrected Compared To 100 Watt Incandescent	
	Initial Lumens	Lamp Only	Lamp and Ballast	Corrected For LLD		Hours Life
25-Watt Incandescent	235	9.4	NA	8.5	.54	2,500
100-Watt Incandescent	1,750	17.5	NA	15.8	1.00	750
100-Watt Incandescent 130 v @ 120 V	1,330	14.9	NA	13.4	.85	2,025
1,000-Watt Incandescent	23,740	23.7	NA	19.7	1.25	1,000
500-Watt T3/CL Tungsten Halogen	10,950	21.9	NA	21.0	1.33	2,000
35-Watt Fluorescent *	3,050		71	63	4.0	20,000
40-Watt Fluorescent **	3,150		66	58	3.7	20,000
110-Watt Fluorescent ***	9,200		73	63	4.0	12,000
400-Watt Mercury ****	23,000		51	40	2.5	24,000
1,000-Watt Mercury ****	63,000		58	38	2.4	24,000
400-Watt Metal Halide	40,000		87	65	4.1	15,000
1,000-Watt Metal Halide *****	110,000		100	80	5.1	10,000
400-Watt High-Pressure Sodium	50,000		111	100	6.2	24,000
1,000-Watt High-Pressure Sodium	140,000		131	117.9	7.5	24,000
180-Watt Low-Pressure Sodium	33,000		150	131.7	8.3	18,000

* 48" Lite White – 2 Lamps Per Ballast (Rapid-Start), or with energy savings ballast 82. lumens/watt.

** 48" Cool White – 2 Lamps Per Ballast (Rapid-Start).

*** 96" (800 ma) Cool White – 2 Lamps Per Ballast (Rapid-Start).

**** Mercury DX (Deluxe White).

***** Other 1,000-Watt Metal Halide Lamps available now are: GE's "I-Line Plus" – 115,000 lumens; and Sylvania's "Super Metalarc" – 125,000 lumens.

LIGHT CONTROL

"Light control" is the term applied to the process of directing the light to the desired location once it is produced by the source. A luminary is a lighting system component that houses the light source and its electrical components and provides for light control. Light control may be accomplished by reflection, by diffusion, or through the application of lenses or prismatic elements.

A range of luminary types is available for each type of light source. They are usually described in terms of candlepower provided in specific directions with specific light sources. The candlepower distribution curves of six types of luminaries used for general illumination are shown in Figure 16. Luminaries play a key role in every lighting system.

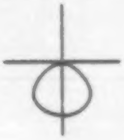
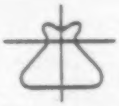
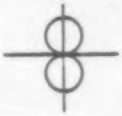
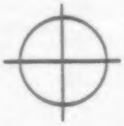
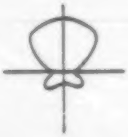
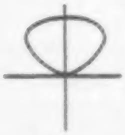
Classification	% Up light	% Down light	Typical candlepower distribution curve
Direct	0-10%	90-100%	
Semi-direct	10-30%	60-90%	
Direct-indirect	40-60%	60-40%	
General diffuse	60-40%	40-60%	
Semi-indirect	60-90%	10-30%	
Indirect	90-100%	0-10%	

Figure 16. Luminary Classifications.

SUMMARY

The selection of light sources for any application is based on four major characteristics of light sources:

1. Efficacy is the ratio of light output to electrical input and is expressed in lumens per watt.
2. The spectral energy distribution describes the relative porportions of different visible wavelengths that are present in the output and indicates the color rendition of the source.
3. Lumen depreciation describes the rate at which the light-producing ability of the source decreases with time.
4. Lifetime is the average useful operating life of the source.

Incandescents offer the lowest efficacies and shortest lives of any sources.

Fluorescents have a much greater efficacy and lifetime and, thus, provide more economical illumination.

High-intensity discharge lamps of several types offer high efficacy, long life and high intensities – although the color rendition is not as good as that of fluorescents.

Low-pressure sodium lamps are the most efficient method of illumination now known. However, their monochromatic nature makes them unsuited for most applications.

EXERCISES

1. The following lamp types are described in this module:
   a. Incandescent
   b. Fluorescent
   c. Mercury-vapor
   d. Metal halide
   e. High-pressure sodium
   f. Low-pressure sodium

   Write a paragraph comparing all of these lamp types according to the following characteristics:
   a. Efficacy
   b. Lifetime
   c. Lumen depreciation
   d. Spectral energy distribution
2. Describe the general construction and method of producing light in each lamp type.
3. Describe the lamp starting mechanisms used with each of the following lamps:
   a. Mercury-vapor
   b. High-pressure sodium
   c. Rapid-start fluorescent
4. Describe the changes that occur in the output of the following lamps when the applied voltage is increased or decreased:
   a. Incandescent
   b. Fluorescent
   c. Mercury-vapor
   d. Metal halide
   e. High-pressure sodium
5. Explain the need for a ballast with some lamps.
6. Explain the term "light control" as it applies to luminaries.

LABORATORY MATERIALS

Footcandle meter
Yardstick or tape measure calibrated in feet
Several light sources
Circular graph paper, one piece for each source measured
Poster board with radial lines from the center at 10° intervals

LABORATORY PROCEDURES

The purpose of this laboratory is to make the necessary measurements and calculations and draw candlepower distribution curves for a number of light sources.

Suggested sources are a bare incandescent bulb, a desk lamp, a fluorescent luminary, and spotlights or flood lights.

In all cases, the measurements must be made in a darkened room. Care must be taken to ensure that only direct illumination from the source being measured reaches the footcandle meter. Reflected light and light from other sources must be minimized. If this is not practical, two measurements may be made: one with the source to be measured ON and one with it OFF. The difference can then be entered in the Data Table as the illumination provided.

Make a Data Table similar to the one given as a sample for each source. Follow the steps outlined below for each.

1. Position the source in a horizontal plane over the poster board so the 0° line of the board is perpendicular to the face of the light source. All measurements may then be made in a horizontal plane at the height of the source. If other geometries are used, all measurements must be made in the same plane and the geometry should be identified in the Data Table.

2. Use the footcandle meter to measure the direct illumination provided by the source along the 0° line at a convenient distance from the source. Measure the distance to the center of the source. Record both the distance and the illumination in the Data Table.
3. Move horizontally to the 10° mark on one side and measure the illumination provided at the same distance. Record the distance to the source and the illumination in the Data Table.
4. Continue this process until measurements have been taken every 10° through an entire circle. Be sure the face of the footcandle meter is pointed directly at the source in every measurement.
5. Divide the illumination in footcandles for each data point by the square of the distance in feet to obtain the candlepower of the source in that direction. Record this in the Data Table.
6. Draw a graph on a piece of circular graph paper with the radial scale calibrated in candlepower. Choose a convenient radial scale to show the candlepower distribution of the source.
7. Classify the distribution of the source according to the criteria given in Figure 16.

DATA TABLE

DATA TABLE.
(Sample)

Description of source:

Sketch of source:

Angle	Illumination (footcandles)	Distance (feet)	Candlepower
0°			
10°			
20°			
30°			
40°			
.*			
.			
.			
350°			

*Note: Ellipsis denotes missing numbers.

REFERENCES

Fundamentals of Commercial and Industrial Lighting. The Electrification Council. N.W. Washington, DC: 1977.

Helms, Ronald N. Illumination Engineering for Energy Efficient Luminous Environments. Englewood Cliffs, NJ: Prentice-Hall Inc., 1980.

Nuckolls, James L. Interior Lighting for Environmental Designers. New York, NY: John Wiley and Sons, 1976.

TEST

Please circle the appropriate answer.

1. The reasons for the popularity of incandescent lamps for many applications include ...
   a. their close approximation of natural lighting.
   b. their relatively long lifetimes.
   c. the lowest lumen depreciation of any lamp except the low-pressure sodium.
   d. Both a and c are correct.
   e. None of the above are correct.
2. If a lamp appears as a bright blue point source, it is a ...
   a. deluxe white mercury lamp.
   b. high-pressure sodium lamp.
   c. quartz-halogen incandescent lamp.
   d. clear mercury lamp.
   e. metal halide lamp.
3. Characteristics of the low-pressure sodium lamp include the ...
   a. highest efficacy of any lamp known.
   b. poorest color rendition of any lamp known.
   c. highest electrical energy to visible conversion efficiency of any lamp.
   d. lowest cost illumination available.
   e. All of the above are correct.

4. When comparing metal halide lamps and high-pressure sodium lamps, the metal halide lamps are superior in ...
   a. efficacy.
   b. lifetime.
   c. lumen depreciation.
   d. color rendition.
   e. Both a and d are correct.
   f. Both b and c are correct.
   g. Both a and d are correct.
5. The lamp with the greatest change in spectral characteristics as voltage changes is the ...
   a. low-pressure sodium lamp.
   b. incandescent lamp.
   c. metal halide lamp.
   d. mercury-vapor lamp.
   e. high-pressure sodium lamp.
6. The efficacy of a high-pressure sodium lamp is ...
   a. almost 30%.
   b. about 130 lumens per watt.
   c. more than twice that of a mercury-vapor lamp.
   d. All of the above are correct.
   e. Only b and c are true.
7. Most fluorescent lamps ...
   a. start in about two seconds.
   b. have external lamp starters.
   c. start insantly when power is applied to the lamp.
   d. employ cold cathodes for rapid starting.
   e. Both a and d are true.

8. Clear mercury lamps are superior to deluxe white mercury lamps in ...
   a. lifetime.
   b. color rendition.
   c. light control.
   d. efficacy.
   e. Both c and d are correct.

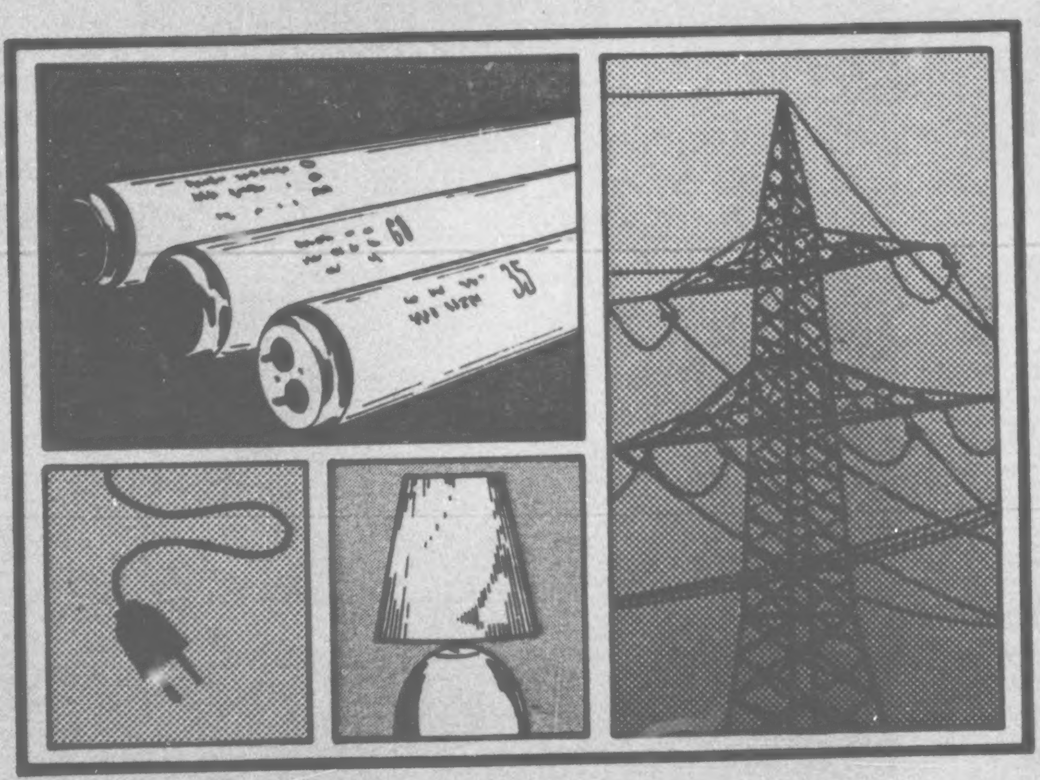
9. Which of the following is always a function of the lamp ballast?
   a. Lamp starting
   b. Current limitation
   c. Power factor correction
   d. Voltage regulation
   e. Both b and c are correct.

10. Which of the following is true of fluorescent lamps?
   a. The lifetime is dependent only on the number of starts.
   b. Lamp efficacy is more dependent on the ambient temperature than for incandescent lamps.
   c. The lumen depreciation is greater than that of incandescent lamps.
   d. Operating at an overvoltage has no effect on lamp lifetime.
   e. Both a and b are true.
   f. All of the above are true.

ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTRICAL POWER AND ILLUMINATION SYSTEMS



MODULE PI-08

EFFICIENCY IN ILLUMINATION SYSTEMS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Increasing energy costs have stimulated interest in energy conservation in every facet of American life. One of the most common – and most inefficient – uses of energy is the production of light energy from electrical energy. Module PI-07, "Light Sources," compared the efficiencies and characteristics of all light sources in common use.

This module, PI-08, "Efficiency in Illumination Systems," discusses energy-efficient illumination systems that save energy and money for the owner.

Topics include efficient lighting design, the efficient use of light sources and luminaries, maintenance programs, and energy-saving tips for lighting system operation.

The cost of incandescent and fluorescent lighting for residential applications is discussed and illustrated, and the methods of calculating lighting costs most often used by industry are presented. This module also explains the relationship of energy waste in lighting systems to the overall energy shortage.

In the laboratory, the student will examine an illumination system and delineate ways in which it might be made more efficient.

PREREQUISITES

The student should have completed Module PI-07, "Light Sources."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. State the percentages of electrical energy and total energy that are used for lighting in this country.
2. State two reasons for the high interest in efficiency of lighting systems.
3. Discuss how lighting systems may be designed for more efficient use of the light that is actually produced. Include the effects of light control, task illumination, and the color of interior surfaces.
4. List the six major light sources presently used and the maximum efficiency that can be achieved with each.
5. Describe the factors affecting the efficiencies of luminaries.
6. Describe the operation of three types of fluorescent luminaries using thermal control and the relative effectiveness of each.
7. Describe the circumstances when a net financial saving may be achieved by turning OFF each of the following light sources and when they should be left ON – even if not in use for a period of time:
    a. Incandescent lights
    b. Fluorescent lights
    c. High-intensity discharge lights
8. Describe the procedure that should be followed for the maximum energy saving when delamping fluorescent luminaries.
9. Describe the two primary functions that are part of every maintenance program for energy-efficient illumination systems.

10. Given the cost of electricity, the wattage of lamps in an illumination system, the average yearly use of the system, the rated lifetime of the lamps, and lamp cost, determine the annual cost of system operation.
11. Given a situation where a more efficient lighting system is to replace an existing system (and all cost information on both systems), determine the time required for the new system to repay its initial cost through savings in operating costs.
12. Given all cost information on a lighting system and the expected lifetime of the system, calculate the lifetime cost of the system and the annual cost of the system.
13. Examine a lighting system and prepare a report describing methods that could be used to make the system more efficient.

ENERGY AND ILLUMINATION

The energy crisis has brought about increased awareness of energy use, waste, and conservation. Every segment of society is encouraged by either government regulation or economic necessity to reduce energy consumption and use energy more efficiently.

One area that has attracted much attention is lighting. Judging from the emphasis sometimes placed on energy waste in lighting, it might seem that the only way to solve the energy crisis is to turn out all the lights. That, however, is not the answer.

This section discusses the energy used for lighting, the relationship of lighting to the energy crisis, and the economic factors that are the reasons for renewed interest in lighting efficiency.

ENERGY REQUIREMENTS FOR ILLUMINATION

About 25% of the energy consumed in this country is used to generate electricity. Approximately one-fifth of the electrical energy produced is used for lighting. Thus, lighting accounts for only 5% of the total energy consumption of the country.

Table 1 is a breakdown of illumination energy use by consumer group. Both percentages of total illumination and total national energy consumption are listed for each consumer group. This table illustrates the point that a great reduction in the use of illumination is not a solution to the nation's energy problems. More efficient lighting is certainly a part of the solution, but much greater energy savings may be attained in other areas.

TABLE 1. USE OF ENERGY FOR ILLUMINATION.

Customer Group	Percent of Lighting Energy Used	Percent of National Energy Consumption
Residential	20%	1.0%
Industrial	20%	1.0%
Stores	20%	1.0%
Offices and Schools	20%	1.0%
Streets and Highways	4%	0.2%
Commercial Outdoor	8%	0.4%
All Others	8%	0.4%
Total	100%	5.0%

Lighting has been emphasized in energy conservation for two reasons. First, lighting is a highly visible form of energy use. Electric light is such a common part of life in this country that it is one of the first areas to come to mind in association with energy waste. Many people (even politicians) assume that wasted light is our greatest energy problem. It is not.

COST OF LIGHTING

The second reason for great interest in the efficiency of lighting systems has a more practical basis. Lighting is one of the areas in which energy conservation is easiest to apply and in which conservation efforts are always rewarded by substantial financial savings.

Efficient lighting is less expensive than inefficient lighting. Since 30 to 50% of the cost of operating a building is usually spent for lighting, a modest increase in illumination efficiency can have a significant effect on overall operating costs.

Reduced energy consumption for lighting brings with it another energy saving. All the energy used for lighting eventually appears as heat in the illuminated area. If the space requires heating, lighting provides part of the necessary heat energy. If the space requires cooling, additional energy is required to remove the heat energy introduced by the lights. In an air conditioned space, approximately one watt-hour of electrical energy is required by the air conditioner to remove the heat produced by each three watt-hours of energy used for lighting.

IMPROVED UTILIZATION OF ILLUMINATION ENERGY

In 1972, the Illuminating Engineering Society (IES) offered twelve recommendations for the better utilization of energy expended for lighting.

1. Design lighting for expected activity. (Light for seeing tasks with less light in surrounding non-working areas.)
2. Design with more effective luminaries and fenestration. (Fenestration is the arrangement of openings, especially of windows, in the wall of a building.)
3. Use efficient light sources (higher lumen/watt output).

4. Use more efficient luminaires.
5. Use thermal-controlled luminaires.
6. Use lighter finishes on ceilings, walls, floors, and furnishings.
7. Use efficient incandescent lamps.
8. Turn OFF lights when not needed.
9. Control window brightness.
10. Utilize daylighting as practicable.
11. Keep lighting equipment clean and in good working condition.
12. Post instructions covering operation and maintenance.

This section discusses practical application of these suggestions.

ENERGY EFFICIENCY IN LIGHTING DESIGN

The IES has published minimum recommended illumination levels for thousands of tasks and areas. In each case, the recommendations are based on the minimum level that is acceptable for the performance of the visual task by persons with normal vision.

Illumination systems are normally designed to provide a higher level of illumination to accommodate abnormal eyes and lumen depreciation of the system (a result of age of the light sources and accumulation of dirt on luminaries). In many cases, recommended levels are greatly exceeded. This results in higher illumination levels than are required. Designing a system for a lower initial light output and improved lumen maintenance often provides adequate illumination at an overall reduced cost.

Light control is a primary concern in the design of efficient lighting systems. The recommended illumination levels are for light on the task. In the past, the tendency has been to illuminate the entire area at the level required for the task.

Current recommendations state that surrounding areas should receive only about one-third the illumination of the task surface. This significantly reduces total illumination requirements, while still providing a comfortable visual environment. The on-task design method requires that the designer be familiar with tasks and task locations in available space. On-task lighting methods may reduce the flexibility of the space for other uses. Some illumination needs may require modular systems and auxillary task lighting.

The color of interior surfaces should always be considered in the design of lighting systems. Whites and light tints reflect more light and increase the overall efficiency of the system. Light colors also provide a more even illumination of the area and reduce the effects of glare and shadows. Under these conditions, slightly less light is actually required for the performance of many visual tasks.

EFFICIENCY AND USE OF LIGHT SOURCES

Module PI-07, "Light Sources," discussed the characteristics of all common light sources. The efficacy of important light sources is indicated by the chart in Figure 1 of this module. Values given are the maximum attainable values for each source.

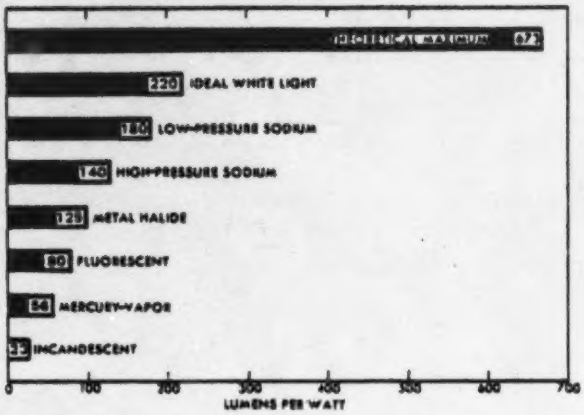


Figure 1. Relative Efficacies of Lamp Sources.

The theoretical maximum efficacy is 673 lumens/watt. This is based on a source that is 100% efficient in converting all its input energy into visible light at 555 nm, the wavelength at which the human eye is most sensitive. If a source converted all its input energy to white light with an even wavelength distribution throughout the visible spectrum, its efficacy would be 220 lumens/watt. Obviously, such sources do not exist. These values are given only for comparison.

The most efficient source is the low-pressure sodium lamp, but it produces all its light at a single wavelength and, thus, cannot be used in any application that requires any color rendition.

The high-pressure sodium lamp has a broader spectral output and only a slightly lower efficacy. Since most of its light is in the yellow-green portion of the spectrum, it also provides poor color rendition.

Metal halide lamps are the highest efficacy sources that provide reasonably good color rendition. Mercury-vapor lamps have the lowest efficacies of any high-intensity discharge (HID) lamps. Their popularity stems primarily from the fact that they have been available longer than any other HID lamp and, thus, have been accepted for many applications that might now be served better by another HID source.

Fluorescent and incandescent lamps are by far the most popular for general illumination. The fluorescent lamp offers both higher efficiency and a much longer lamp life. It is a far more economical light source than incandescent lamps in most applications.

Incandescent lamps are still widely-used in residential illumination and are common in other areas as well. In most cases, incandescents should be replaced by fluorescents. However, if incandescents are used, they should be used in the most efficient manner possible. The efficacy of incandescent lamps increases with lamp wattage. A 100-watt incandescent bulb produces 2.2 times the light as a 60-watt bulb. Thus, the most economical use of incandescent lamps is to use fewer and larger lamps.

In selecting light sources, the efficacy of the source is almost never the primary consideration. Spectral characteristics are most often the first criteria to be satisfied. An effort is then made to determine the most efficient source that provides the necessary quality of light.

EFFICIENCY OF LUMINARIES

The overall efficiency of any illumination system is greatly affected by the efficiencies of the luminaries used.

A wide variety of designs and materials are available. Both the candlepower distribution and reflectivity of the luminary must be considered. An appropriate luminary should be selected to direct light onto the task – rather than to areas where light will not be used.

Several materials may be used in luminaries for light dispersion. As an example of luminary efficiency, Table 2 lists the relative efficiencies of materials used for light dispersion in fluorescent luminaries. In each case, the material is introduced between the source and the illuminated area. The first three elements listed are transmitting elements; the last two are reflective grids suspended below the lamps. All efficiencies given are relative to the glass prismatic element.

TABLE 2. EFFICIENCIES OF LIGHT DISPERSION ELEMENTS.

Type of Dispersion Element	Relative Efficiency (%)
Glass prismatic	100
Acrylic prismatic	99
Dished acrylic	87
1-1/2" plastic louver	67
1/2" white aluminum louver	52

THERMAL-CONTROLLED FLUORESCENT LUMINARIES

Widespread use of fluorescent lamps for commercial and office lighting, combined with increased interest in energy conservation, has led to the use of several types of fluorescent luminaries that are designed to reduce the heat load of the illuminated area.

Figure 2 shows an ordinary luminary and its heat distribution pattern. About half of the heat an ordinary luminary produces is transmitted directly into the illuminated area. The other half of the heat enters the ceiling plenum and eventually shows up as heat gain in the building. This heat gain must be overcome by the air conditioning system.

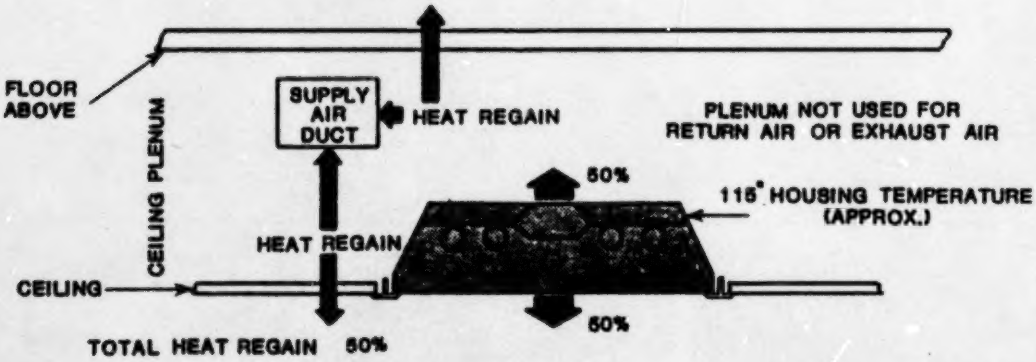

FLOOR ABOVE
CEILING PLENUM
SUPPLY AIR DUCT
HEAT REGAIN
PLENUM NOT USED FOR RETURN AIR OR EXHAUST AIR
50%
115° HOUSING TEMPERATURE (APPROX.)
HEAT REGAIN
CEILING
50%
TOTAL HEAT REGAIN 50%

Figure 2. Heat Gain From Ordinary Fluorescent Luminary.

Figure 3 shows the improvement that can be made by simply using the ceiling plenum as the air return duct. This reduces the direct heating of the space to 40%, and reduces regain to 20 to 30%. Air flow over the luminaries, and a small flow of air around the sides of the luminaries, removes any heat remaining in the return air flow. This system requires no special luminaries. Actual energy savings depend upon the percentage of the return air that is exhausted from the building.

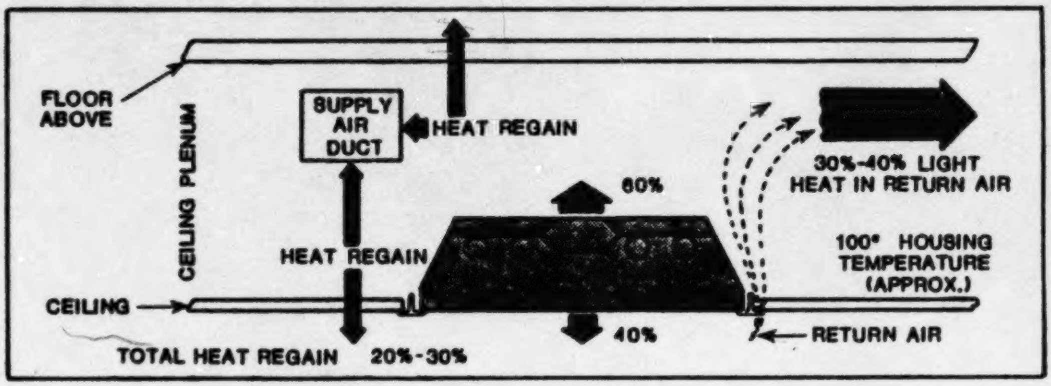

FLOOR ABOVE
CEILING PLENUM
SUPPLY AIR DUCT
HEAT REGAIN
30%-40% LIGHT HEAT IN RETURN AIR
60%
100° HOUSING TEMPERATURE (APPROX.)
HEAT REGAIN
CEILING
40%
RETURN AIR
TOTAL HEAT REGAIN 20%-30%

Figure 3. Luminary in Ceiling Return Air Plenum.

Figure 4 shows a more efficient system. This system uses a luminary that is designed to return air to the ceiling plenum through slots in the luminary. This method results in better heat transfer and reduces the heat gain of the illuminated space by about 10%.

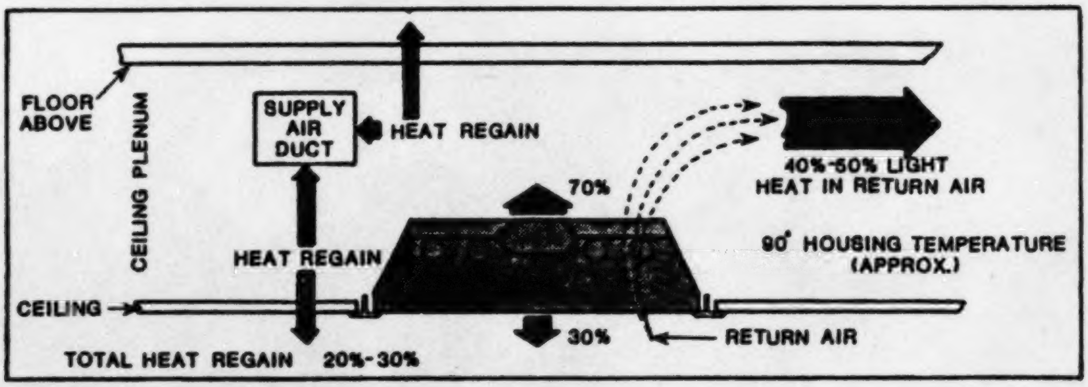

FLOOR ABOVE
CEILING PLENUM
SUPPLY AIR DUCT
HEAT REGAIN
40%-50% LIGHT HEAT IN RETURN AIR
70%
90° HOUSING TEMPERATURE (APPROX.)
HEAT REGAIN
CEILING
30%
RETURN AIR
TOTAL HEAT REGAIN 20%-30%

Figure 4. Return Air Through Luminary.

The water-cooled luminary, shown in Figure 5, is by far the most efficient in reducing heat gain. Water coils on the back of the luminary carry away about 70% of the heat energy produced. Another 5% may be removed if the water-cooled luminary is mounted in a ceiling that acts as a return air plenum.

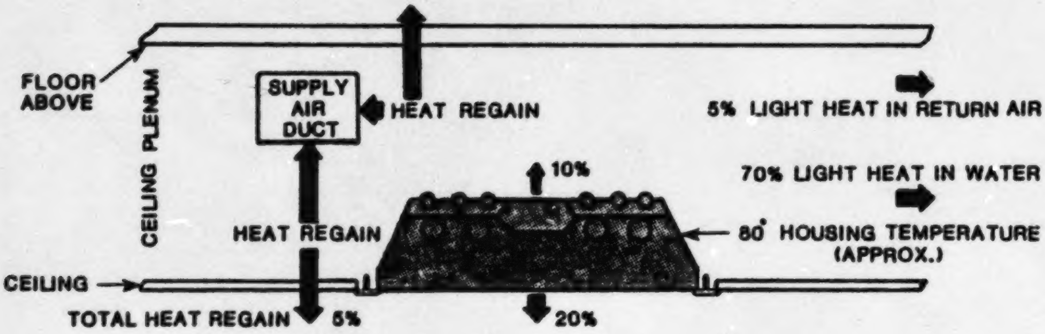

FLOOR ABOVE
CEILING PLENUM
SUPPLY AIR DUCT
HEAT REGAIN
5% LIGHT HEAT IN RETURN AIR
10%
70% LIGHT HEAT IN WATER
HEAT REGAIN
80° HOUSING TEMPERATURE (APPROX.)
CEILING
TOTAL HEAT REGAIN 5%
20%

Figure 5. Water-Cooled Luminary.

Another advantage of this system is that it does not represent a heat load on the air conditioning system. The heat energy recovered from the lights can be used to heat water. Lowering the luminary temperature also results in increased lighting efficiency (by about 15%).

TURNING LIGHTS OFF

The simplest – and often the most effective – method of reducing lighting expenditures is to turn lights OFF when they are not needed. The lifetime of incandescent lamps is not greatly affected by the number of lamp starts. Thus, incandescent lamps should always be turned OFF when they are not needed, even if they are to be turned back ON in only a few minutes. This practice alone can save a significant portion of residential lighting costs.

The lifetime of a fluorescent lamp decreases as the average operating time per lamp start decreases. Lamp life is specified at an average of three hours of operation for each lamp start. Figure 6 shows the variations in fluorescent lamp life as a function of hours of operation per start.

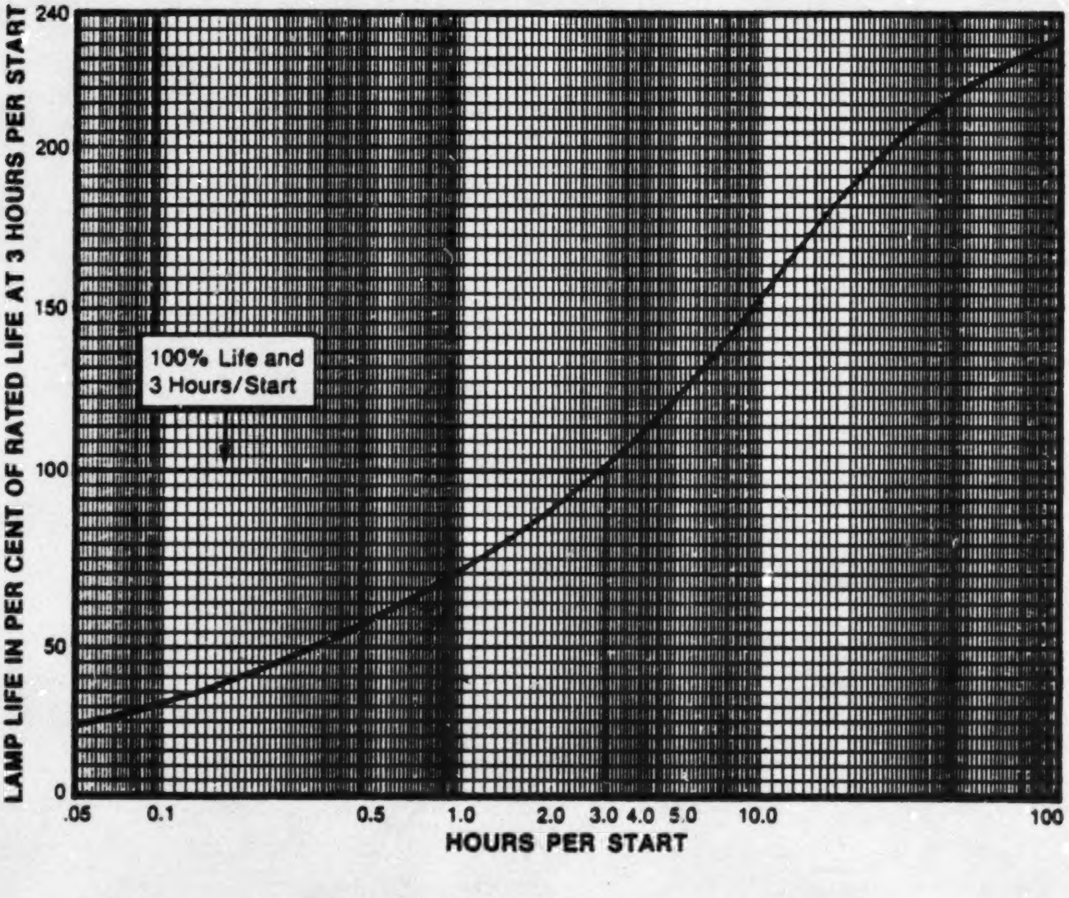


Figure 6. Fluorescent Lamp Life as a Function of Running Hours.

Fluorescent lamps fail because the electron-emitting coatings of the cathodes are gradually depleted. This occurs most strongly at lamp start-up. Turning fluorescent lamps OFF for only a minute or two does not save much energy, but it does reduce lamp lifetime. It is generally economical to turn fluorescents OFF if they are not to be used for 15 minutes. An off-time of less than 15 minutes will probably cost as much in shortened lamp life as it saves in energy costs.

High-intensity discharge lamps require a warm-up time of 1-1/2 to 10 minutes, depending on the lamp type. Some HID lamps require as long as 15 minutes for restart after being turned OFF. The lifetime of such lamps is specified at an average of five hours of operation per lamp start. More frequent starting may reduce lamp life by as much as one-third. Thus, HID lamps are not usually turned OFF unless they are to remain OFF for at least half an hour.

In some applications, light timers that turn certain lights OFF at certain times may result in a significant savings. Another popular method is to perform maintenance and cleaning tasks at reduced illumination levels. Several control methods may be employed for this.

Every other luminary in a continuous fluorescent strip may be turned OFF, or two of the lamps in each four-lamp luminary may be turned OFF. In the latter case, the center two bulbs should be used for reduced illumination for the most efficient illumination.

In older installations in which the illumination greatly exceeds the necessary level, a procedure called delamping may be used. This consists of simply removing half of the bulbs from the luminaries. It is an effective method of reducing lighting costs if done properly. If done improperly, it can be expensive.

Fluorescent lamps are usually wired so that one ballast serves two bulbs. If one of these bulbs is removed, the other will continue to operate, but the ballast will burn out in only a few hours. Thus, delamping of fluorescent lamps should always be done so that both lamps of a ballast are removed at one time. The ballast will continue to consume power, even though the lamp is no longer in place. Power consumption is typically 7 watts per tube. A slight increase in savings may be made by disconnecting the ballasts from the power line when the lamps are removed.

USE OF DAYLIGHT

A fenestration is any opening that allows light from the exterior environment to enter the interior environment. Fenestrations are classified as windows and toplights, depending on their location. Neither is an energy-efficient method of illumination for most applications. In cold environments, the heat loss through such openings more than offsets the savings gained in lighting. In hotter climates, the heat gain that must be overcome by the air conditioner system is more costly than even the least efficient electrical lighting system. Double pane and reflective glass reduces such heat flow, but even these measures cannot make daylight as economical as artificial light. The most energy-efficient building is one without windows.

Windows are included in modern structures for psychological and aesthetic purposes. When used, windows should be designed to reduce or eliminate glare. Direct sunlight is usually undesirable. All fenestrations should be fitted with light control in the form of blinds, shades, or some other light-blocking device.

EQUIPMENT MAINTENANCE

A well-planned equipment maintenance program is essential to the efficient operation of any lighting system. In the past, most maintenance consisted of changing a bulb when it burned out and maybe wiping the dust off the luminary every now and then. This is obviously not a very efficient procedure.

The lumen output of all lamps depreciates as the lamp ages. Some lamps have little depreciation. For other lamps, lumen depreciation is a significant problem. The depreciation for specific lamp types may be found in Module PI-07, "Light Sources."

In most cases, relamping is economical after about 70% of the rated lifetime of the lamps. All lamps in a system are replaced at once, even though the lamps may have some useful life remaining. This maintains the illumination at the proper level and reduces maintenance costs by eliminating the need for continuous spot replacement of lamps.

Table 3 gives the approximate time between relamping for various sources. This is based on relamping after 70% of the rated lifetime, with an assumed operation of 12 hours continuously per day (or about 3,000 hours per year). The higher maintenance labor costs of incandescent systems can be seen in Table 3. If operating time per start is high, fluorescents have the longest lifetimes of any lamp type.

TABLE 3. RELAMPING SCHEDULE.

Light Source	Rated Life (hours)	Relamping Interval (months)
Fluorescent	26,000	72
Mercury-vapor	24,000	67
High-pressure sodium	20,000	56
Metal halide	15,000	42
Incandescent	2,000	6

The second major maintenance problem to be overcome in lighting systems is the accumulation of dirt and dust on the luminaries. Figure 7 shows the luminary dirt depreciation (LDD) curves for a particular class of luminaries. Specifications are illustrated according to five operating conditions, ranging from very clean to very dirty. Such curves

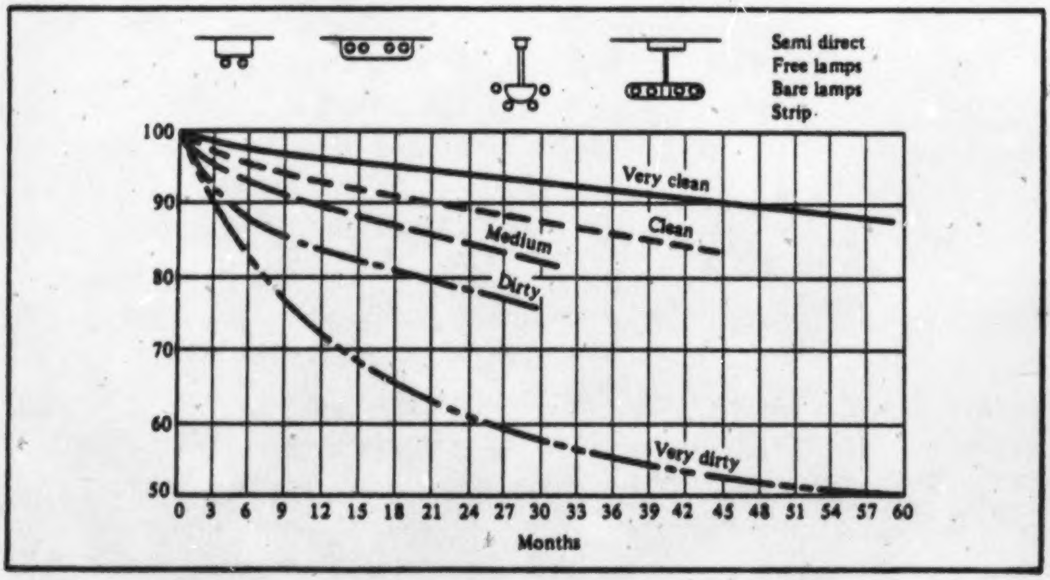


Figure 7. Typical Luminary Dirt Depreciation Curve.

are available for all luminary types and are used both in the selection of luminaries for particular locations and for establishing maintenance schedules. In clean environments with all lamp types except incandescents, luminary cleaning is required more frequently than lamp replacement for good system efficiency.

COST OF ILLUMINATION

The total cost of an illumination system includes the initial cost of the installation, the cost of energy to operate the system, maintenance and relamping costs, and the cost in interest on money borrowed to install the system. A complete analysis of lighting budgets is beyond the scope of this module. This section discusses basic concepts and some simple examples of methods of comparing lighting costs.

INCANDESCENT VERSUS FLUORESCENT FOR RESIDENTIAL LIGHTING

The following example compares the cost of incandescent and fluorescent lighting for a residential application. This example has been chosen to illustrate the savings of fluorescent lighting under the least favorable conditions.

EXAMPLE A: INCANDESCENT VERSUS FLUORESCENT LIGHTING.

Given: A residential application requires an illumination of 4,500 lumens. The average operating time per lamp start is 15 minutes. The two most efficient light sources to be considered are:

Source A: Three 100-watt incandescent bulbs with a rated life of 750 hours and an initial total output of 5,250 lumens. (This allows for lumen depreciation.) Bulbs cost $0.78 each.

Source B: Two 40-watt fluorescent tubes with a rated life of 18,000 hours (with 3 hours run time per start) and an initial total output of 6,300 lumens. Including ballasts, the total power consumption is 95.5 watts. Tubes cost $1.95 each.

Assume an electrical rate of $0.05/kWh. The lighting system is to be operated for 1,000 hours per year.

Find: Yearly operating cost (lamps + energy) for each light source

Solution: a. Lamp cost per year ...

From Figure 6, the lifetime of the fluorescent lamps drop to 45% of the rated lifetime (or 8,100 hours) because of the frequency of lamp starts.

The lamp cost per year for each source may be determined by multiplying the cost per

Example A. Continued.

lamp, times the number of lamps, times the ratio of running time per year to lamp life:

Incandescent

$$\text{Lamp Cost} = (3)(\$0.78)\left(\frac{1{,}000\ \text{hr}}{750\ \text{hr}}\right)$$
$$= \$3.12/\text{yr}.$$

Fluorescent

$$\text{Lamp Cost} = (2)(\$1.95)\left(\frac{1{,}000\ \text{hr}}{8{,}100\ \text{hr}}\right)$$
$$= \$0.48/\text{yr}.$$

Incancescent bulbs cost 6.5 times as much in the long run.

b. Energy cost per year ...

The energy cost per year may be determined by multiplying the energy consumption in kilowatts, times the hours of operation in one year, times the electrical utility rate.

Incandescent

$$\text{Energy Cost} = (0.300\ \text{kW})(1{,}000)(\$0.05)$$
$$= \$15.00/\text{yr}.$$

Fluorescent

$$\text{Energy Cost} = (0.0955)(1{,}000)(\$0.05)$$
$$= \$4.78/\text{yr}.$$

Incandescent bulbs cost a little over three times as much to operate per year.

Example A. Continued.

c. Total Cost ...

Incandescent	Fluorescent
$18.12/yr.	$5.26/yr.

Fluorescents will save $12.86/year over incandescents, or 71% of the cost of incandescent light. Two 40-watt fluorescent lamps also produce more light than three 100-watt incandescents, are subject to less lumen depreciation, and add less heat load to the space if air conditioned. Even under unfavorable conditions, fluorescents are the best buy.

PAY-BACK COSTING

Whenever one lighting system is being replaced by another more efficient system, the question most often asked is: How long before the new equipment investment pays for itself? Pay-back costing is a method of comparing lighting systems. The initial cost of the new system is compared to operational cost savings to determine how long it will take to recover the investment. Example B illustrates pay-back costing.

EXAMPLE B: PAY-BACK COSTING.

Given: Light source A of Example A is already in existence. Light source A is to be removed and replaced by light source B. The new fixture costs \$36.00 and will cost \$10.00 to install.

Find: Time required for pay-back of the initial investment

Solution: Initial investment in light source B = \$46.00

Savings per year = \$12.86

$$\text{Time for pay-back} = \frac{\$46.00}{\$12.86/\text{yr}} = 3.58 \text{ years.}$$

The system will pay for itself in approximately 43 months, less than half the expected lifetime of the first set of lamps.

Recall that Examples A and B are based on 100-watt incandescent lamps with good efficacy (for incandescents) and poor operating conditions for fluorescents. There are very few situations in which incandescents are more economical than fluorescents.

LIFETIME COSTING

For new installations, or situations where several alternatives are available for replacement of existing inefficient lighting, lifetime costing is applied. Lifetime costing compares two lighting systems by determining the total lifetime costs for each system during its expected life. This method is applied to most commercial and industrial lighting systems and is illustrated in Example C. Since most industrial and commercial systems are installed with borrowed money, the interest on the initial cost must be considered. For simplicity in Example C, the lifetime of the system is taken to be 10 years and the yearly owning cost (initial cost plus interest divided by 10) is assumed to be 20% of the initial cost.

EXAMPLE C: LIFETIME COSTING OF ILLUMINATION SYSTEMS.

Given: An obsolete incandescent lighting system is to be replaced with a more energy-efficient system. The choice is between metal halide lamps and high-pressure sodium lamps. Both have acceptable color characteristics. The system is to be chosen on the basis of the minimum lifetime cost. If metal halide lamps are used, thirty-eight 1,000-watt lamps will be necessary. Because of their higher efficacy, only twenty-eight 1,000-watt high-pressure sodium lamps are required for the same illumination. (Note: A detailed cost analysis of each item will not be made in this example. The intent is to demonstrate the method of lifetime costing, not the costs of details such as individual maintenance procedures or lamp fixtures.)

Find: Total annual cost of each system

Example C. Continued.

Solution:

	System I 1,000-Watt High-Pressure Sodium	System II 1,000-Watt Metal Halide
Number of Luminaires	28	38
Net Cost of Luminaires	$ 7,257.60	$ 6,213.00
Wiring	949.20	1,242.60
Installation	840.00	1,140.00
Initial Lamps	2,318.40	1,744.20
Total Initial Cost	$11,365.20	$10,339.80
Yearly Owning Cost	$2,273.04	$2,067.96

System II represents an initial savings of $1,025.40 and a savings of $205.08 in yearly owning cost.

Relamping and Cleaning

Using group relamping and 6,000 burning hours/year for 10 years.

	System I	System II
Number of Replacement Periods	5	9
Cost per Lamp	$ 82.80	$ 45.90
Lamp Group Cost	2,318.40	1,744.20
Labor per Relamping (Includes Cleaning)	140.00	140.00
Cost per Occurrence	2,458.40	1,884.20
Average Yearly Cost (Cost per occurrence x number of occurrences/10)	$1,229.20	$1,695.78
Energy Costs		
Lamps, kW	28	38
Ballast loss, kW	5.6	7.6
kW total	33.6	45.6
kWh @ 6,000 hrs/yr.	201,600.	273,600
Cost @ 3.5c per kWh	$7,056	$9,576
Total Owning and Operating Costs		
Total Yearly Owning	$ 2,273.04	$ 2,067.96
Total Yearly Operating		
a. Relamping (Average)	1,229.20	1,695.78
b. Energy	7,056.00	9,576.00
Total Yearly Owning & Operating	$10,558.24	$13,339.74

Difference $2,781.50

System II represents an annual savings of $2,781.50 and a lifetime savings of $27,815.00.

SUMMARY

About 20% of the electrical energy consumed in this country and 5% of the total energy consumed is used for electrical lighting. Thus, more efficient lighting alone will do little to improve the energy situation. High interest in the efficiencies of lighting systems is a result of the following factors:

- Lighting is a highly-visible use of energy and is, therefore, bound to attract attention.
- Lighting is one area in which energy may be conserved at a substantial saving to the consumer using existing technology.
- The lighting budget is a significant portion of the operating costs of most buildings.
- Residential lighting systems make high use of low-efficiency incandescent sources and, thus, represent the area of greatest lighting energy waste.

Energy-efficient lighting systems require the use of more efficient light sources and luminaries, better utilization of the light produced, regular maintenance programs, and an integration of the lighting system into the overall energy utilization plan for the facility.

The cost of lighting may be calculated on the basis of the time required for a more efficient system to pay for itself through reduced energy and maintenance costs — or the cost per year — of the lighting, averaged over the lifetime of the system.

EXERCISES

1. Write a paragraph describing how each of the following factors affects the efficiency and cost of an illumination system:
   a. Light control for task illumination
   b. Color of walls, ceilings, and floors
   c. Dispersion elements used in luminaries
   d. Accumulation of dust on luminaries
   e. Scheduled group replacement of lamps
   f. Use of thermal-controlled fluorescent luminaries
   g. Use of higher-wattage incandescent lamps
2. Describe the necessary precautions in delamping fluorescent lighting systems. Describe what must be done to achieve maximum energy savings.
3. Describe the effect of each of the following light sources on the total building heat load:
   a. Incandescent lamps
   b. Fluorescent lamps mounted in a ceiling that serves as a return air plenum
   c. Water-cooled fluorescent luminaries
   d. Use of daylight to reduce lighting costs
4. Draw a bar chart showing the maximum efficacies of the six most commonly used light sources.
5. Describe factors that affect when the following light sources should be turned OFF for maximum savings:
   a. Incandescent lamps
   b. Fluorescent lamps
   c. HID lamps

6. Rework Examples A and B with an average running time of ...
    a. 1 hour per lamp start.
    b. 3 hours per lamp start.
    c. 10 hours of lamp start.
7. Using the cost data given in Example A, determine the energy cost to run the following lamps for their rated lifetimes. Compare this figure to the lamp costs.
    a. 100-watt incandescent
    b. 40-watt fluorescent
8. Assume an electrical energy cost of \$0.05/kWh and a 10-year system lifetime. Calculate the lifetime costs of the following illumination systems. Assume that each system is installed with borrowed money, and that each system is operated for 2,500 hours per year. Lamps are replaced at 70% of their lifetime.
    a. Incandescent system consisting of twenty 100-watt lamps with an average life of 750 hours. Initial system cost = \$210. Replacement lamps cost \$0.78 each. Labor cost is \$10 for each relamping.
    b. Fluorescent system consisting of twelve 40-watt lamps with an average life of 18,000 hours. (Each lamp and ballast consumes 47.75 watts.) Initial system cost = \$350. Replacement lamps cost \$1.80 each. Labor cost is \$10 for each relamping.

LABORATORY MATERIALS

IES tables of recommended levels of illumination
Footcandle meter
Illumination system to be evaluated

LABORATORY PROCEDURES

The purpose of this laboratory exercise is to evaluate the efficiency of an illumination system and estimate the annual cost of the system. Any system can be used, but the lighting in the classroom or laboratory is suggested.

1. Describe the system to be examined in the Data Table. Enter all available data on operating hours, lamp cost, electricity cost, and lamp lifetime. Estimate the values that are not available based on lamp characteristics.
2. Consult the IES tables to determine the recommended level of illumination for the visual tasks and enter this figure in the Data Table.
3. Measure the illumination level at various points in the area. Enter the illumination on the task and the illumination of surrounding areas in the Data Table.
4. Complete the necessary calculations to determine the approximate annual operating cost of the system. Do not include the labor costs of maintenance.
5. Examine the system for inefficiencies. List suggestions for increasing system efficiency in the Data Table.
6. Write a report on the efficiency of the system. Include the annual cost of the system, suggestions for improved efficiency, and the estimated savings that will result.

DATA TABLE

DATA TABLE

Description of system:

Recommended level of illumination: ____________________

Measured levels of illumination: ______________________

on task: ______________________

surrounding areas: ______________________

Lamp type: ________________________________

Number of lamps: ___________________________

Total wattage of lamps and ballasts: __________________

Annual operating time: ______________________

Lamp lifetime: _____________________________

Replacement lamp cost: _____________________

Electrical energy rate: ____________________

Electrical energy cost per year: ______________________

Lamp replacement cost per year: _______________________

Total system cost per year: ___________________________

Suggestions for increased efficiency:

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Fundamentals of Commercial and Industrial Lighting. The Electrification Council. N.W. Washington, D.C., 1977.

Helms, Ronald N. Illumination Engineering for Energy Efficient Luminous Environments. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1980.

Nuckolls, James L. Interior Lighting for Environmental Designers. New York: John Wiley and Sons, 1976.

TEST

Please circle the appropriate answer.

1. Illumination systems use what percentage of the electrical energy produced in this country each year?
   a. 1%
   b. 5%
   c. 20%
   d. 25%
   e. 30%
2. Which of the following practices is least likely to result in an overall energy saving?
   a. Delamping fluorescent luminaries
   b. Using natural daylight for illumination
   c. Replacing incandescent lamps with fluorescent lamps
   d. Leaving fluorescent lamps ON if the area is unoccupied for 30 minutes.
   e. Designing systems for task illumination.
3. Fluorescent lamps have a maximum efficacy of ...
   a. 23 lumens/watt.
   b. 50 lumens/watt.
   c. 80 lumens/watt.
   d. 120 lumens/watt.
   e. 180 lumens/watt.
4. The cost of energy to operate a fluorescent lamp for its rated lifetime is usually ...
   a. slightly less than the lamp cost.
   b. slightly greater than the lamp cost.
   c. 20 to 30 times the lamp cost.
   d. over 100 times the lamp cost.
   e. about 1,000 times the lamp cost.

5. The use of water-cooled luminaries for fluorescent lamps results in a large overall energy savings because ...
   a. less heat must be removed by the air conditioning system.
   b. waste heat from the lamps can be used to heat water.
   c. they result in improved lamp efficacy.
   d. All of the above are correct.
   e. Only a and b are correct.
6. The lifetime of which of the following lamps is not affected by frequent starting?
   a. Incancescent
   b. Fluorescent
   c. Mercury-vapor
   d. High-pressure sodium vapor
   e. Both a and d are correct.
7. The most cost-effective maintenance programs for lighting systems must include ...
   a. periodic cleaning of luminaries.
   b. periodic replacement of all lamps as a group.
   c. spot replacement of only those lamps that are burned out.
   d. Both a and b are correct.
   e. Both a and c are correct.
8. The lamp with the longest rated lifetime for long periods of operation per lamp start is the ...
   a. high-pressure sodium lamp.
   b. metal halide lamp.
   c. mercury-vapor lamp.
   d. fluorescent lamp.
   e. incandescent lamp.

9. The method of calculating the cost of illumination for most industrial systems is the ...
   a. lifetime costing method.
   b. pay-back costing method.
   c. energy utilization costing method.
   d. system maintenance costing method.
   e. None of the above are correct.

10. If a lamp consumes 1,000 watts of power at 3.5¢/kWh and its rated life is 18,000 hours, the cost of operating the lamp for its rated life is ...
    a. $6.30.
    b. $63.
    c. $630.
    d. $6,300.
    e. $63,000.